BEFORE THE OIL CONSERVATION COMMISSION
COMMENCING NOVEMBER 12, 2024

CASE NO. 23580

WILD EARTH GUARDIANS – PFAS RULEMAKING

PART 1

NEW MEXICO OIL AND GAS ASSOCIATION

TABLE OF CONTENTS
NMOGA EXHIBIT A THROUGH NMOGA EXHIBIT D10.39

STATE OF NEW MEXICO
DEPARTMENT OF ENERGY, MINERALS AND NATURAL RESOURCES
OIL CONSERVATION COMISSION

IN THE MATTER OF PROPOSED
AMENDMENT TO THE COMMISSION'S
RULES TO ADDRESS CHEMICAL DISCLOSURE
AND THE USE OF PERFLUOROALKYL AND
POLYFLUOROALKYL SUBSTANCES AND
THEIR USE IN OIL AND GAS EXTRACTION,
19.15.2, 19.15.7, 19.15.14, 19.15.16 AND 19.15.25 NMAC **CASE NO. 23580**

HEARING PACKAGE
TABLE OF CONTENTS

of PFAS

- NMOGA Exhibit E4: Hammel, 2022 – Implications of PFAS Definitions
- NMOGA Exhibit E5: Pennoyer, 2023 – Uknown Organofluorine Mixtures in US Adult Serum
- NMOGA Exhibit E6: Henry, 2018 – A Critical Review of the Application of Polymer of Low Concern and Regulatory Criteria for Fluoropolymers
- NMOGA Exhibit E7: Korzeniowski, 2022 - A Critical Review of the Application of Polymer of Low Concern Regulatory Criteria to Fluoropolymers II
- NMOGA Exhibit E8: USEPA, 2021b – National PFAS Testing Strategy
- NMOGA Exhibit E9: Goodrum – Application of a Framework for Grouping and Mixtures Toxicity Assessment
- NMOGA Exhibit E10: USEPA, 2024b – FINAL – Human Health Toxicity Assessment for PFOA and Related Salts
- NMOGA Exhibit E11: USEPA, 2024a – FINAL – Human Health Toxicity Assessment for PFOS and Related Salts
- NMOGA Exhibit E12: 2021, PSR Report – Fracking with “Forever Chemicals”
- NMOGA Exhibit E13: Connor, 2021 – Comment on Fracking with “Forever Chemicals”
- NMOGA Exhibit E14: USEPA, 2024c – Instruction for Reporting PFAS Under TSCA Section 8(a)(7)
- NMOGA Exhibit E15: Vedagiri, 2018 – Ambient Levels of PFOS and PFOA
- NMOGA Exhibit E16: Zhu, 2022 – Vermont-wide Assessment of Anthropogenic Background Concentrations of PFAS in surface soils
- NMOGA Exhibit E17: NRC, 1983 – Risk Assessment in the Federal Government
- NMOGA Exhibit E18: NRC, 1994 – Science and Judgment in Risk Assessment
- NMOGA Exhibit E19: USEPA, 1989 – Risk Assessment Guidance
- NMOGA Exhibit E20: USEPA, 1997 – Ecological Rish Assessment
- NMOGA Exhibit E21: USEPA, 1999 – Issuance of Final Guidance
- NMOGA Exhibit E22: NMED, 2017- Risk Assessment Guidance for Site Investigations
- NMOGA Exhibit E23: NMED, 2022 – Risk Assessment Guidance for Site Investigations
- NMOGA Exhibit E24: Entine, 2011 – Scared to Death
- NMOGA Exhibit E25: USEPA, 2021a – The SALT Framework
- NMOGA Exhibit E26: Calloway, 2020 – Exploring Community Psychosocial Stress Related to PFAS Contamination
- NMOGA Exhibit E27: NRC, 2009 – Science and Decisions
- NMOGA Exhibit E28: Brooks & Patel – Psychological Consequence of the Flint Water Crisis
- NMOGA Exhibit E29: ITRC, 2020 – Risk Communication Toolkit

WG EXHIBIT 1

FIRST AMENDED PROPOSED RULE

PROPOSED AMENDMENTS TO PART 2

TITLE 19 NATURAL RESOURCES AND WILDLIFE
CHAPTER 15 OIL AND GAS
PART 2 GENERAL PROVISIONS FOR OIL AND GAS OPERATIONS

****

19.15.2.7 DEFINITIONS: These definitions apply to 19.15.2 NMAC through 19.15.39 NMAC.

C. Definitions beginning with the letter "C".

~~(4) **"Chemical"** means any element, chemical compound, or mixture of elements or chemical compounds that has a specific name or identity, including a Chemical Abstracts Service number.~~
(5) ~~**"Chemical disclosure list"** means a list of all chemicals used in downhole operations at a well site.~~
~~(4)~~(6) **"Cm/sec"** means centimeters per second.
~~(5)~~(7) **"CPD"** means central point delivery.
~~(6)~~(8) **"Combination multiple completion"** means a multiple completion in which two or more common sources of supply are produced through a combination of two or more conventional diameter casing strings cemented in a common well bore, or a combination of small diameter and conventional diameter casing strings cemented in a common well bore, the conventional diameter strings of which might or might not be a conventional multiple completion.
~~(7)~~(9) **"Commission"** means the oil conservation commission.
~~(8)~~(10) **"Commission clerk"** means the division employee the director designates to provide staff support to the commission and accept filings in rulemaking or adjudicatory cases before the commission.
~~(9)~~(11) **"Common purchaser for gas"** means a person now or hereafter engaged in purchasing from one or more producers gas produced from gas wells within each common source of supply from which it purchases.
~~(10)~~(12) **"Common purchaser for oil"** means every person now engaged or hereafter engaging in the business of purchasing oil to be transported through pipelines.
~~(11)~~(13) **"Common source of supply"**. See pool.

NMOGA Exhibit A

~~(12)~~(14) **"Condensate"** means the liquid recovered at the surface that results from condensation due to reduced pressure or temperature of petroleum hydrocarbons existing in a gaseous phase in the reservoir.
~~(13)~~(15) **"Contiguous"** means acreage joined by more than one common point, that is, the common boundary is at least one side of a governmental quarter-quarter section.
~~(14)~~(16) **"Conventional completion"** means a well completion in which the production string of casing has an outside diameter exceeding 2.875 inches.
~~(15)~~(17) **"Conventional multiple completion"** means a completion in which two or more common sources of supply are produced through one or more strings of tubing installed within a single casing string, with the production from each common source of supply completely segregated by means of packers.
~~(16)~~(18) **"Correlative rights"** means the opportunity afforded, as far as it is practicable to do so, to the owner of each property in a pool to produce without waste the owner's just and equitable share of the oil or gas in the pool, being an amount, so far as can be practically determined, and so far as can be practicably obtained without waste, substantially in the proportion that the quantity of recoverable oil or gas under the property bears to the total recoverable oil or gas in the pool, and for the purpose to use the owner's just and equitable share of the reservoir energy.
~~(17)~~(19) **"Cubic feet of gas or cubic foot of gas"** means that volume of gas contained in one cubic foot of space and computed at a base pressure of 10 ounces per square inch above the average barometric pressure of 14.4 psi (15.025 psi absolute), at a standard base temperature of 60 degrees fahrenheit.

Justification – NMOGA has removed both the definitions of (1) "chemical" and (2) "chemical disclosure list" for the reasons outlined in its Pre-Hearing Statement and the testimony of Drs. Anderson and Richardson, which NMOGA incorporates here.

- Principal among its reasons for removing the term "chemical," is that the present rulemaking specifically concerns PFAS in hydraulic fracturing fluids not the use of every potential, indiscriminate "chemical" in hydraulic fracturing. Accordingly, NMOGA has removed the broad, sweeping, and unspecific term "chemical" from the proposed definitions, which does not inform this rulemaking.
- Likewise, NMOGA has removed the term "chemical disclosure list" from the proposed amendments, for a multitude of reasons, including, but not limited to, the fact that operators must already disclose the constituents in their hydraulic fracturing fluids in the FracFocus chemical registry databases pursuant to 19.15.16.19(B) NMAC. Adding a "chemical disclosure list" to the rules is redundant of existing FracFocus disclosure requirements and is unnecessary.

D. Definitions beginning with the letter "D".

~~(6) **"Downhole operations"** means oil and gas production operations that are conducted underground.~~
~~(6)~~(7) **"Downstream facility"** means a facility associated with the transportation (including gathering) or processing of gas or oil (including a refinery, gas plant, compressor station or crude oil pump station); brine

production; or the oil field service industry.
~~(7)~~(8) **"DRO"** means diesel range organics.

Justification – NMOGA has removed the definition of "downhole operations" from the proposed amendments, as further outlined in its Pre-Hearing Statement and the testimony of Drs. Anderson and Richardson, which NMOGA incorporates here.

- WEG's definition is vague and unduly broad. As proposed, it includes a wide array of well activities not subject to this rulemaking and unrelated to hydraulic fracturing. WEG's definition of "downhole operations" is so broad—including nearly all activities conducted in the subsurface, such as running seismic logs—that it is virtually meaningless.
- Further, this rulemaking is concerned particularly with hydraulic fracturing of wells and any proposed, additional definitional terms should be tailored to this scope.
- Because WEG's definition of "downhole operations" (1) is so broad it is virtually meaningless and (2) because it is unrelated to this rulemaking addressing hydraulic fracturing, NMOGA has, appropriately, removed the term "downhole operations" from the proposed amendments.

****

H. Definitions beginning with the letter "H".

(6) "Hydraulic fracturing treatment" means all stages of the treatment of a well by the application of hydraulic fracturing fluid under pressure, which treatment is expressly designed to initiate or propagate fractures in an underground geologic formation to enhance the production of oil and gas.
~~(6)~~(7) **"H_2S"** means hydrogen sulfide.

****

I. Definitions beginning with the letter "I"

(8) "Intentionally added PFAS" means PFAS that are deliberately added during the manufacture of a chemical production to serve an intended function in the final product.

Justification – NMOGA has added the definition of "intentionally added PFAS," as further summarized in its Pre-Hearing Statement and the testimony of Drs. Anderson and Richardson, which NMOGA incorporates here.

- "Intentionally added" is needed to properly capture both (1) the reality that PFAS are ubiquitous and could be present in the environment despite not be contained in hydraulic fracturing fluid, and (2) the intended scope of this rulemaking, which is to prohibit the use of hydraulic fracturing fluids that contain PFAS.

****

P. Definitions beginning with the letter “P”.

(3) “PFAS ~~chemicals”~~ ~~means a perfluoroalkyl or polyfluoroalkyl substance with at least one fully fluorinated carbon atom~~ means a perfluoroalkyl or polyfluoroalkyl substance with two or more sequential fully fluorinated carbon atoms.

~~(3)~~(4) **“Pit”** means a surface or sub-surface impoundment, man-made or natural depression or diked area on the surface. Excluded from this definition are berms constructed around tanks or other facilities solely for safety, secondary containment and storm water or run-on control.

~~(4)~~(5) **“Playa lake”** means a level or nearly level area that occupies the lowest part of a completely closed basin and that is covered with water at irregular intervals, forming a temporary lake.

~~(5)~~(6) **“Pool”** means an underground reservoir containing a common accumulation of oil or gas. Each zone of a general structure, which zone is completely separated from other zones in the structure, is covered by the word pool as used in 19.15.2 NMAC through 19.15.39 NMAC. “Pool” is synonymous with “common source of supply” and with “common reservoir”.

~~(6)~~(7) **“Potential”** means a well’s properly determined capacity to produce oil or gas under division-prescribed conditions.

~~(7)~~(8) **“Ppm”** means parts per million by volume.

~~(8)~~(9) **“PQL”** means practical quantitation limit.

~~(9)~~(10) **“Pressure maintenance”** means the injection of gas or other fluid into a reservoir, either to maintain the reservoir’s existing pressure or to retard the reservoir pressure’s natural decline.

~~(10)~~(11) **“Produced water”** means a fluid that is an incidental byproduct from drilling for or the production of oil and gas.

~~(11)~~(12) **“Producer”** means the owner of a well or wells capable of producing oil or gas or both in paying quantities.

~~(12)~~(13) **“Product”** means a commodity or thing made or manufactured from oil or gas, and derivatives of oil or gas, including refined crude oil, crude tops, topped crude, processed crude petroleum, residue from crude petroleum, cracking stock, uncracked fuel oil, treated crude oil, fuel oil, residuum, gas oil, naphtha, distillate, gasoline, kerosene, benzene, wash oil, lubricating oil and blends or mixtures of oil or gas or a derivative thereof.

~~(13)~~(14) **“Proration day”** consists of 24 consecutive hours that begin at 7:00 a.m. and end at 7:00 a.m. on the following day.

~~(14)~~(15) **“Proration month”** means the calendar month that begins at 7:00 a.m. on the first day of the month and ends at 7:00 a.m. on the first day of the next succeeding month.

~~(15)~~(16) **“Proration period”** means for oil the proration month and for gas the 12-month period that begins at 7:00 a.m. on January 1 of each year and ends at 7:00 a.m. on January 1 of the succeeding year or other period designated by general or special order of the division.

~~(16)~~(17) **“Proration schedule”** means the division orders authorizing the production, purchase and transportation of oil, casinghead gas and gas from the various units of oil or of gas in allocated pools.

~~(17)~~(18) **“Proration unit”** means the area in a pool that can be effectively and efficiently drained by one well as determined by the division or commission (see Subsection B of Section 70-2-17 NMSA 1978) as well as the area assigned to an individual well for the purposes of allocating allowable production pursuant to a prorationing order for the pool.
~~(18)~~(19) **“Prospective spacing unit”** means a hypothetical spacing unit that does not yet have a producing well.
~~(19)~~(20) **“PVC”** means poly vinyl chloride.
~~(20)~~(21) **“Psi”** means pounds per square inch.

Justification – NMOGA has revised WEG’s proposed definition of “PFAS,” as discussed in its Pre-Hearing Statement and the testimony of Drs. Anderson and Richardson, both of which NMOGA incorporates herein.

- NMOGA removed the modifier “chemicals” from WEG’s proposed term “PFAS Chemicals.” PFAS are in and of themselves chemicals, therefore, WEG’s use of “Chemicals” as part of this definition is redundant and wholly unnecessary.
- NMOGA has, additionally, revised the definition of “PFAS” to be consistent with (1) federal and other regulations defining “PFAS,” (2) other states’ regulations defining PFAS, and (2) the generally accepted scientific definition of “PFAS,” which requires at least two or more fully fluorinated carbon atoms.

****

T. Definitions beginning with the letter “T”.

~~(7) **“Trade secret”** means information, including a formula, pattern, compilation, program, device, method, technique or process, that:~~
~~(1) derives independent economic value, actual or potential, from not being generally known to and not being readily ascertainable by proper means by other persons who can obtain economic value from its disclosure or use; and~~
(2) ~~is the subject of efforts that are reasonable under the circumstances to maintain its secrecy.~~
~~(7)~~(8) **“Treating plant”** means a plant constructed for wholly or partially or being used wholly or partially for reclaiming, treating, processing or in any manner making tank bottoms or other waste oil marketable.
~~(8)~~(9) **“Tribal lands”** means those lands for which the United States government has a trust responsibility to a native American tribe or a member of a native American tribe. This includes reservations, pueblo land grants, tribal trust lands and individual trust allotments.
~~(9)~~(10) **“Tribal leases”** means those leases of minerals or interests in or rights to minerals for which the United States government has a trust responsibility to a native American tribe or a member of a native American tribe.
~~(10)~~(11) **“Tribal minerals”** means those minerals for which the United States government has a trust responsibility to a native American tribe or a member of a native American tribe.
~~(11)~~(12) **“True vertical depth”** means the difference in elevation between the ground level at the surface location of the well and the deepest point in the

well bore.
~~(12)~~(13) **"Tubingless completion"** means a well completion in which the production string of casing has an outside diameter of 2.875 inches or less.
~~(13)~~(14) **"Tubingless multiple completion"** means completion in which two or more common sources of supply are produced through an equal number of casing strings cemented in a common well bore, each such string of casing having an outside diameter of 2.875 inches or less, with the production from each common source of supply completely segregated by cement.

Justification – NMOGA has removed the term "trade secret" from the proposed definitional terms, as analyzed in detail in its Pre-Hearing Statement, incorporated herein.

- Although the WEG's proposed definition of "trade secret" is consistent with the New Mexico Uniform Trade Secret Act, NMSA 1978, §§ 57-3A-1 to 57-3A-7 (1989), the Commission has no authority to enact regulations that, when applied, mandate operators publicly disclose trade secreted hydraulic fracturing fluid components.
- Because NMOGA removed WEG's proposed revisions to 19.15.14.10, 19.15.16.17, 19.15.16.19 NMAC, the applicable Parts of the rules applying the "trade secret" definition, NMOGA has correspondingly removed the definitional term of the same.

****

U. Definitions beginning with the letter "U".

~~(3) **"Undisclosed chemicals"** means either chemicals that are listed without a Chemical Abstracts Service number in the FracFocus database pursuant to 19.15.16.19(B) NMAC, or if a safety data sheet lists ingredients that comprise less than one-hundred percent of the whole chemical product, those chemicals that make up any unlisted portion of a chemical product on a safety data sheet.~~

~~(3)~~(4) **"Unit of proration for gas"** consists of such multiples of 40 acres as may be prescribed by division-issued special pool orders.

~~(4)~~(5) **"Unit of proration for oil"** consists of one 40-acre tract or such multiples of 40-acre tracts as may be prescribed by division-issued special pool orders.

~~(5)~~(6) **"Unorthodox well location"** means a location that does not conform to the spacing requirements division rules establish.

~~(6)~~(7) **"Unstable area"** means a location that is susceptible to natural or human-induced events or forces capable of impairing the integrity of some or all a division-approved facility's structural components. Examples of unstable areas are areas of poor foundation conditions, areas susceptible to mass earth movements and karst terrain areas where karst topography is developed because of dissolution of limestone, dolomite or other soluble rock. Characteristic physiographic features of karst terrain include sinkholes, sinking streams, caves, large springs and blind valleys.

~~(7)~~(8) **"Upstream facility"** means a facility or operation associated with the exploration, development, production or storage of oil or gas that is not a downstream facility.

Justification – NMOGA has removed the term "undisclosed chemicals" from the proposed definitional terms, as analyzed in detail in its Pre-Hearing Statement, incorporated herein.

- WEG includes the definition of "undisclosed chemicals" in relation to the proposed regulatory amendments that would require full disclose of all constituents or additives in hydraulic fracturing fluids without regard to claims of trade secret protections.
- As discussed above regarding WEG's proposed definition of "trade secret," the Commission has no authority to require operators to waive their claims of trade secret. For the reasons stated above in 19.5.2.7 regarding the definition of "trade secret" and in the Pre-Hearing Statement, incorporated herein by reference, NMOGA has removed the term "undisclosed chemicals" from WEG's proposed revised regulations.

W. Definitions beginning with the letter "W".

~~(8) "Well site" means the area that is disturbed by oil and gas operations within the boundaries of the lease.~~
~~(8)~~(9) **"Wellhead protection area"** means the area within 200 horizontal feet of a private, domestic fresh water well or spring used by less than five households for domestic or stock watering purposes or within 1000 horizontal feet of any other fresh water well or spring. Wellhead protection areas does not include areas around water wells drilled after an existing oil or gas waste storage, treatment or disposal site was established.
~~(9)~~(10) **"Wetlands"** means those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions in New Mexico. This definition does not include constructed wetlands used for wastewater treatment purposes.
~~(10)~~(11) **"Working interest owner"** means the owner of an operating interest under an oil and gas lease who has the exclusive right to exploit the oil and gas minerals. Working interests are cost bearing.
~~(11)~~(12) **"WQCC"** means the New Mexico water quality control commission.

Justification – NMOGA has removed the term "well site" from the proposed definitional regulations, as analyzed in detail in its Pre-Hearing Statement, incorporated herein.

- WEG uses the term in one location, at 19.15.16.19(D), in its proposed amendments. Because NMOGA recommends rejecting WEG's amendments at 19.15.16.19(D), it has correspondingly removed the definition of "well site" from 19.15.2.7.

****

PROPOSED AMENDMENTS TO PART 7

19.15.7.16 WELL COMPLETION OR RECOMPLETION REPORT AND LOG (Form C-105):

A. Within 45 days following the completion or recompletion of a well, the operator shall file form C-105 with the division accompanied by a summary of special tests conducted on the well, including drill stem tests.~~, and the chemical disclosure list.~~ In addition, the operator shall file a certification that no PFAS was intentionally used in the completion or recompletion of the well, ~~undisclosed chemicals or PFAS were used in the completion or recompletion of the well~~, a copy of electrical and radio-activity logs run on the well with form C-105. If the division does not receive form C-105 with attached certification~~, chemical disclosure list,~~ logs and summaries within the specified 45-day period, the division shall withhold the allowable authorizations for the well or suspend injection authority, as appropriate, until the operator has complied with 19.15.7.16 NMAC.

B. In the case of a dry hole, a complete record of the well on form C-105, or if applicable form C-103, with the attachments listed in Subsection A of 19.15.7.16 NMAC shall accompany the notice of intention to plug the well, unless previously filed. The division shall not approve the plugging report or release the bond the operator has complied with 19.15.7.16 NMAC.

C. The division shall not keep form C-105, or if applicable form C-103, and accompanying attachments confidential unless the well's owner requests in writing that the division keep it confidential. Upon such request, the division shall keep these data confidential for 60 ~~90~~ days from the date of the well's completion, provided, however, that the report, logs and other attached data shall ~~may~~, when pertinent, be introduced in a public hearing before division examiners, the commission or in a court of law, regardless of the request that they be kept confidential.

D. If there is a change in the information provided under this part, the operator must submit the change to the division within 30 days after the date the operator first knew of the change.

E. The division shall retain each form C-105 and form C-103 indefinitely.

[19.15.7.16 NMAC - Rp, 19.15.13.1105 NMAC, 12/1/2008; A, 9/26/2017; A, 8/23/2022]

Justification – NMOGA has made the above-identified revisions to 19.15.7.16 NMAC.

- NMOGA supports requiring operators to certify that no intentionally added PFAS were used in their hydraulic fracturing operations.
- As outlined in its (1) Pre-Hearing Statement and testimony of Drs. Anderson and Richardson, incorporated herein by reference, and (2) above in 19.15.2.7, definitional terms, the target of this rulemaking is a prohibition on the use of PFAS-containing hydraulic fracturing fluids. NMOGA recommends the revisions to 19.15.7.16 to properly capture the focus of this rulemaking.

****

PROPOSED AMENDMENTS TO PART 14

19.15.14.9 APPLICATIONS: An operator shall file a complete form C-101 and complete form C-102 with the division and meet the following requirements, if applicable: an applicant for a permit to drill a well within the corporate limits of a city, town or village shall give notice to the duly constituted governing body of the city, town or village or its duly authorized agent and certify on form C-101 that it gave such notice;

~~A.~~ an applicant for a permit to drill in a quarter-quarter section containing an existing well or wells operated by another operator shall concurrently file a plat or other acceptable document locating and identifying the well or wells, furnish a copy of the application to the other operator or operators in the quarter-quarter section and certify on form C-101 that it furnished the copies;

~~B.~~ an applicant for a permit to drill, deepen, or plug back shall certify that they will not intentionally introduce any PFAS containing hydraulic fracturing fluids in hydraulic fracturing operations of the well; and ~~utilize any hydraulic fracturing undisclosed chemicals or PFAS in downhole operations of the well ; and~~

~~C~~ D**.** an applicant for a permit to operate a well in a spacing or proration unit containing an existing well or wells operated by another operator shall also comply with Subsection B of 19.15.15.12 NMAC.

[19.15.14.9 NMAC – Rp, 19.15.3.102 NMAC and 19.15.13.1101 NMAC, 12/1/2008]

Justification – NMOGA has made the above-identified strike throughs and revisions to 19.15.7.16 NMAC.

- NMOGA supports requiring operators to certify that no PFAS-containing fracturing fluids were used in hydraulic fracturing operations in New Mexico.
- As analyzed in its (1) Pre-Hearing Statement and testimony of Drs. Anderson and Richardson, incorporated herein by reference, and (2) identified above in 19.15.2.7, definitional terms, the target of this rulemaking is a prohibition on the use of PFA-containing fracturing fluids in hydraulic fracturing operations. NMOGA recommends the revisions to 19.15.14.9, as it has drafted them, to properly capture the focus of this intended PFAS prohibition.

19.15.14.9 APPROVAL OR DENIAL OF A PERMIT TO DRILL, DEEPEN OR PLUG BACK:

A. The director or the director's designee may deny a permit to drill, deepen or plug back if the applicant is not in compliance with Subsection A of 19.15.5.9 NMAC and shall deny a permit to drill, deepen, or plug back~~, or any permit authorizing the transport of nondomestic waste, including produced water~~, if the applicant does not provide the certification required by Subsection C of 19.15.14.9~~ or provides a false certification.~~ In determining whether to grant or deny the permit, the director or the director's designee shall consider such factors as whether the non-compliance with Subsection A of 19.15.5.9 NMAC is caused by the operator not meeting the financial assurance requirements of 19.15.8 NMAC, being subject to a division or commission order finding the operator to be in violation of an order requiring corrective action, having a penalty assessment that has been unpaid for more than 70 days since the issuance of the order assessing the penalty or having more than the allowed number of wells out of compliance with 19.15.25.8 NMAC. If the non-compliance is caused by the operator having more than the allowed number of wells not in compliance with 19.15.25.8 NMAC, the director or director's designee shall consider the number of wells not in compliance, the length of time the wells have been out of compliance and the operator's efforts to bring the wells into compliance.

Justification – NMOGA has struck through portions of proposed 19.15.14.9, namely language in WEG's proposed amendments that includes revisions outside the scope of this rulemaking and that improperly attempt to redefine produced water as a "nondomestic waste."

- As analyzed in more detail in its (1) Pre-Hearing Statement and testimony of Drs. Anderson and Richardson, incorporated herein by reference, and (2) enumerated above in 19.15.2.7, the target of this rulemaking is a prohibition on the use of PFAS-containing fracturing fluids in hydraulic fracturing. This rulemaking has nothing to do with "transport" of either produced water or nondomestic waste and has not been properly noticed to consider any such issues. NMOGA recommends the revisions to proposed 19.15.14.9 to properly capture the scope of this rulemaking, which targets PFAS-containing fracturing fluids.
- Secondly, as discussed in the Pre-Hearing Statement, to the extent that WEG's amendments in 19.15.14.9 attempt to redefine or equate produced water with or to "nondomestic waste," such amendment is contrary to existing statutory and regulatory definitions that provide separate and differing definitions of each term, and is a procedurally and legally improper method by which to attempt to redefine these terms.

****

PROPOSED AMENDMENTS TO PART 16

TITLE 19 NATURAL RESOURCES AND WILDLIFE
CHAPTER 15 OIL AND GAS
PART 16 DRILLING AND PRODUCTION

19.15.16.17 COMPLETION OPERATIONS, SHOOTING AND CHEMICAL TREATMENT OF WELLS:

~~A. If Completing, shooting, fracturing or treating a well has the potential to negatively impact the producing formation, injection interval, communicates with other strata, casing or casing seat or may create underground waste or contaminate fresh water, the operator shall within five working days notify in writing the division and proceed with diligence to use the appropriate method and means for rectifying the damage.~~

~~(1) diligence shall include but is not limited to verifying casing integrity and isolation of strata. This can include pressure testing in accordance with 19.15.25 NMAC, performing casing integrity logs, cement bond logs and any other means determined necessary by the operator or required by the division.~~

~~(2) If damage from the shooting, fracturing or treating of a well has the potential to impact surface or groundwater, the operator will test for all chemicals disclosed in previous downhole operations and will use a third party, verified laboratory to conduct any in appropriate testing necessary to verify any potential impact. The testing shall include all chemicals used in the well and may also include but is not limited to PFAS, chemicals listed in20.6.2. NMAC and chemicals listed in 19.15.29.11.A.(5)(e) NMAC. The division can elect to request more robust sampling than what is proposed by the operator if deemed necessary due to the nature of the potential chemicals.~~

~~(3) If it is deemed there is an impact to surface or groundwater the operator shall report the impact as a major release in accordance with 19.15.29 NMAC and respond accordingly.~~

~~(4) If testing reveals the presence of PFAS or undisclosed chemicals, the Division may revoke authorization to operate upon consideration of whether the current operator or a previous well owners' operations contributed to the presence of PFAS or undisclosed chemicals.~~

~~D. If completing, shooting, fracturing or chemical treating results in the well's irreparable injury the division may require the operator to properly plug and abandon the well and take any necessary actions to mitigate any resulting impacts.~~

A. If shooting, fracturing or treating a well injures the producing formation, injection interval, casing or casing seat and may create underground waste or contaminate fresh water, the operator shall within five working days notify in writing the division and proceed with diligence to use the appropriate method and means for rectifying the damage. If shooting, fracturing or chemical treating results in the well's irreparable injury the division may require the operator to properly plug and abandon the well; or

B. If a well integrity event occurs from the hydraulic fracturing of a well and causes a loss of containment outside the target strata or damages the well casing or casing seat or may create underground waste or contaminate fresh water, the operator shall within five working days notify in writing the division and proceed with diligence to use the appropriate method and means for rectifying the loss of containment or any damage.

(1) Diligence shall include, but is not limited to, verifying casing integrity and isolation of the target strata. This can include pressure testing in accordance with 19.15.25 NMAC, performing casing integrity logs, cement bond logs, and any other means determined necessary by the operator or required by the division.

(2) If a well integrity event of the type enumerated in paragraph B of this section occurs and has a reasonable probability to contaminate surface or groundwater, then:

(a) the division may request that the supplier, service company, or operator who submitted the FracFocus hydraulic fracturing disclosure, in accordance with NMAC 19.15.16.19 (B), submit to the division additional information regarding the specific identity and/or Chemical Abstracts Service (CAS) number of any additive or chemical ingredient(s) used in the hydraulic fracturing operations, including confidential, proprietary, or trade-secreted information. Any confidential, proprietary, or trade-secreted information must be submitted to the division in an envelope clearly marked "confidential." Should the division receive a request for disclosure of any information marked "confidential," including, but not limited to, requests under NMSA 1978,§§ 14-2-1 to 14-2-12, for disclosure of the information, the division will forward the request to the party claiming the information is confidential. Not later than five business days after receiving the request, the party claiming confidentiality shall submit to the division a verification that the information remains wholly or partially confidential, identifying any portions of the information that is no longer confidential, and setting out the specific facts and legal authority supporting nondisclosure. If requested by the party seeking disclosure of the information, the division may provide to the party seeking disclosure of the information, the name, contact information, and/or other identifying information of the party claiming the information is confidential.

(b) the division may require the operator to test surface or groundwater within the immediate vicinity of the well integrity event and the division may require the operator to sample for the following contaminants:

(i) all contaminants identified on Table I of 19.15.29.12, and as may be amended; and

(ii) all chemicals disclosed in the FracFocus hydraulic fracturing disclosure in accordance with 19.15.16.19(B) NMAC and which are also identified as groundwater contaminants in 20.6.2.3103 NMAC, and as may be amended.

(c) The operator must use an appropriately certified, third-party laboratory to conduct the commensurate sampling and analysis; and will engage with the division to gain access to valid sampling points within the immediate vicinity of the well integrity event.

C. If the division determines that the well integrity event caused a major release, as defined in 19.15.29 NMAC, then the operator shall report the release in accordance with 19.15.29 NMAC or has polluted, as defined in 19.15.30 NMAC, subsurface water then the operator shall abate the pollution in accordance with 19.15.30 NMAC as applicable.

D. If the well integrity event from completing, shooting, fracturing or treating a well results in the well's irreparable injury the division may require the operator to properly plug and abandon the well and take any necessary actions to mitigate harm to human health, animal or plant life, or property.

[19.15.16.17 NMAC - Rp, 19.15.3.115 NMAC, 12/1/2008; 19.15.16.17 NMAC - Rn, 19.15.16.16 NMAC, 2/15/2012]

Justification – NMOGA has made several revisions to WEG's amendments to 19.15.16.17.

- NMOGA has struck through the majority of WEG's proposed amendments to 19.15.16.17, the rationale for which is further detailed and discussed in NMOGA's (1) Pre-Hearing Statement, and both (2) Drs. Anderson and Richardson's testimony.
- Part A and Proposed Part B – NMOGA has proposed adding Part B to this rule, in recognition of feedback from the OCD that it prefers to leave Part A largely unchanged because of the current scope of Part A, which includes offset fracturing. Consequently, NMOGA proposes new language at Part B to specifically and more particularly address well integrity events from hydraulic fracturing treatment(s), while also leaving Part A largely unchanged from its existing language.
- Part B(1) – NMOGA only had small changes to this Part B(1), which included modifying the WEG language from "strata" to "target strata" to more accurately identify the geophysical location meant to be addressed by the regulation.
- Part B(2) – NMOGA recommends further modifications to WEG's proposed language because WEG's language is imprecise and, therefore, creates ambiguity. NMOGA's language at Part B(2), on the other hand, clearly conveys that it is a well integrity event that triggers possible follow-on action and what, specifically, that/those action(s) must be should a well integrity event occur.
- Part B(2)(a) – NMOGA's revisions recognize that FracFocus is and remains the depository for hydraulic fracturing disclosures. Additionally, NMOGA has attempted to strike the right balance in Part B(2)(a) by creating a process—similar ones of which are in place in both Alaska and Wyoming—whereby, trade secreted information can remain so, while at the same time, if a well integrity event were to occur, the Division could confidentially obtain *all* necessary information regarding the constituents in the hydraulic fracturing operations that caused the event. Adopting NMOGA's revisions to Part B(2)(a) also recognizes the strong public policy for and legal protections ensuring against disclosure of proprietary, business confidential, trade-secreted information in New Mexico.
- Part B(2)(b)(i)-(ii) – the revisions to these parts expressly identify (1) the media-to-be tested, (2) the geographic scope to be-examined, and (3) the contaminants to be sampled and analyzed should a well integrity event occur. Moreover, this language tracks the language of both existing WQCC regulations at 20.6.2.3103 and OCD regulations at 19.15.16.29 and 19.15.16.30 to ensure continuity and clarity in the regulatory requirements.
- Part B(2)(c) – WEG's proposed language regarding a "third party verified laboratory" is not the generally accepted terminology to discuss analytical laboratories. Furthermore, it fails to recognize that laboratories are "certified" to perform certain analytical methods based on requirements from regulatory agencies, such as the US Environmental Protection Agency. Accordingly, NMOGA has modified the language in Part B(2)(c) to reflect the generally accepted terminology regarding analytical laboratories.
- Part C – NMOGA revised Part C to clearly articulate that should a well integrity event occur, the remedy for such event is to be found in existing OCD regulations at 19.15.16.29 and 19.15.16.30, respectively.

- Part D – NMOGA added the language "human health, animal, or plant life," which is both more defined than WEG's language, consistent with the Division's enumerated powers in Section 70-2-12(B), and tracks language used elsewhere in existing OCD and WQCC regulations.

19.15.16.19 LOG, COMPLETION AND WORKOVER REPORTS

A. **Completion report.** Within 45 days after the completion of a well drilled for oil or gas, or the recompletion of a well into a different common source or supply, the operator shall file a completion report with the division on form C-105. For the purpose of 19.15.16.19, a hole drilled or cored below fresh water that penetrates oil- or gas-bearing formations or that an owner drills is presumed to be a well drilled for oil or gas. The operator shall signify on form C-105, or alternatively on form C-103, whether the well has been hydraulically fractured.

B. **Hydraulic fracture disclosure.** For a hydraulically fractured well, the operator shall also complete and file with the FracFocus chemical disclosure registry a completed hydraulic fracturing disclosure within 45 days after completion, recompletion, or other hydraulic fracturing treatment of the well. The hydraulic fracturing disclosure shall be completed on a then current edition of the hydraulic fluid product component information form published by FracFocus and shall include complete and correct responses disclosing all information called for by the FracFocus form, provided that:

(1) -the division does not require the reporting of information beyond the material safety data sheet data as described in 29 C.F.R. 1910.1200, with the exception of section 19.15.16.17(B)(2) for events requiring the confidential disclosure to the Division of otherwise proprietary, trade secret, or confidential business information;

(2) (1) the division does not require the reporting or disclosure of proprietary, trade secret or confidential business information; and

(3) (2) the division shall download and archive New Mexico FracFocus submissions on a quarterly basis.

C. If the FracFocus chemical disclosure registry is temporarily inoperable, the operator of a well on which hydraulic fracturing treatment(s) were performed shall file the information required by the then most recent FracFocus form with the division along with Well Completion Report (form C-105) or Sundry Notice (form C-103) reporting the hydraulic fracture treatment and file the information on the FracFocus internet website when the website is again operable. If the FracFocus chemical disclosure registry is discontinued or becomes permanently inoperable, the operator shall continue filing the information with the division until otherwise provided by rule or order.

~~**D.** On or before [DATE], an operator shall provide the chemical disclosure list to:~~

~~**(1)** All owners of minerals that are being developed at the well site;~~

~~**(2)** All surface owners, building unit owners, and residents, including tenants of both residential and commercial properties, that are within five thousand two hundred and eighty feet of the well site;~~

~~**(3)** The State Land Office if the state owns minerals that are being developed at the well site;~~

~~**(4)** The federal bureau of land management if the United States owns the minerals that are being developed at the well site;~~
~~**(5)** To any tribe if the minerals being developed at the well site are within the exterior boundary of that tribe's reservation and are subject to the jurisdiction of the division;~~
~~**(6)** All schools, child care centers, and school governing bodies within five thousand two hundred and eighty feet of the well site;~~
~~**(7)** Police departments, fire departments, emergency service agencies, and first responder agencies that have a jurisdiction that includes the well site;~~
~~**(8)** Local governments that have a jurisdiction within five thousand two hundred and eighty feet of the well site;~~
~~**(9)** The administrator of any public water system that operates:~~
  ~~**(a)** A surface water public water system intake that is located fifteen stream miles or less downstream from the well site;~~
  ~~**(b)** A groundwater source under the direct influence of a surface water public water system supply well within five thousand two hundred and eighty feet of the well site; and~~
  ~~**(c)** A public water system supply well completed within five thousand two hundred and eighty feet of the well site; and~~

- ~~The chemical disclosure list must be disclosed to the above parties within thirty days after the operator's chemical disclosure to the division.~~

Justification – NMOGA has made several revisions to WEG's amendments to 19.15.16.19.

- As outlined in more detail in its (1) Pre-Hearing Statement and testimony of Drs. Anderson and Richardson, incorporated herein by reference, and (2) discussed above in 19.15.2.7, this rulemaking has been noticed to enact a prohibition on the use of PFAS-containing fracturing fluids in hydraulic fracturing operations and the disclosure of PFAS constituents, with limited exceptions, in the FracFocus chemical registry, disclosures that are already required under New Mexico law. NMOGA recommends the revisions to 19.15.14.9 to properly confine this rulemaking to the scope clearly identified in WEG's Application and the PFAS Public Notice.
- NMOGA recommends the addition at 19.15.14.9(B)(1), specifically, to be consistent with its proposed amendments at 19.15.16.17.
- Additionally, NMOGA recommends removing WEG's proposed additional language at 19.15.16.19(D). As Dr. Anderson testifies, and incorporated here, making chemical disclosures in the manner WEG proposes in this Part does not advance public health or create positive community outcomes. On the contrary, making such disclosures out of context, without additional information can cause negative physical and mental health effects for community members, amongst other negative outcomes.
- NMOGA supports the continued disclosure of hydraulic fracturing fluids, with limited exceptions, discussed above in 19.15.16.19(B)(1)-(3), to the FracFocus chemical registry, which is available to the public, free of cost, for anyone interested in such information. Continuing to require disclosures be made in FracFocus provides a transparent process that also does not unnecessarily burden communities with information for which they have no context. At the same time, however, for those interested or curious the disclosure information is readily available, free of cost.

****

PROPOSED AMENDMENTS TO PART 25

19.15.25.14 DEMONSTRATING MECHANICAL INTEGRITY:

A. An operator may use the following methods of demonstrating internal casing integrity for ~~for casing investigations,~~ casing repairs and wells to be placed in approved temporary abandonment:

(1) the operator may set a cast iron bridge plug within 100 feet of uppermost perforations or production casing shoe, load the casing with inert fluid and pressure test to 500 psi surface pressure with a pressure drop of not more than 10 percent over a 30 minute period;

(2) the operator may run a retrievable bridge plug or packer to within 100 feet of uppermost perforations or production casing shoe, and test the well to 500 psi surface pressure for 30 minutes with a pressure drop of not greater than 10 percent over a 30 minute period; or

(3) the operator may demonstrate that the well has been completed for less than five years and has not been connected to a pipeline.

B. During the testing described in Paragraphs (1) and (2) of Subsection A of 19.15.25.14 NMAC the operator shall:

(1) open all casing valves during the internal pressure tests and report a flow or pressure change occurring immediately before, during or immediately after the 30 minute pressure test;

(2) top off the casing with inert fluid prior to leaving the location;

(3) report flow during the test in Paragraph (2) of Subsection A of 19.15.25.14 NMAC to the appropriate division district office prior to completion of the temporary abandonment operations; the division may require remediation of the flow prior to approving the well's temporary abandonment.

C. An operator may use any method approved by the EPA in 40 C.F.R. section 146.8(c) to demonstrate external casing and cement integrity for wells to be placed in approved temporary abandonment.

D. The division shall not accept mechanical integrity tests or logs conducted more than 12 months prior to submittal.

E. The operator shall record mechanical integrity tests on a chart recorder with a maximum two hour clock and maximum 1000 pound spring, which has been calibrated within the six months prior to conducting the test. Witnesses to the test shall sign the chart. The operator shall submit the chart with form C-103 requesting approved temporary abandonment.

F. The division may approve other testing methods the operator proposes if the operator demonstrates that the test satisfies the requirements of Subsection B of 19.15.25.13 NMAC.

[19.15.25.14 NMAC - Rp, 19.15.4.203 NMAC, 12/1/2008]

Justification – NMOGA has revised WEG's amendments to 19.15.25.14, as discussed in its Pre-Hearing Statement and incorporated here.

- WEG's amendment adds the term, "casing investigation" to 19.15.24.14(A). However, WEG fails to define this term or otherwise use it in context, which creates regulatory ambiguity. It is unclear what a "casing investigation" is; how it may differ from a “casing integrity test”; and under what circumstances the OCD would require a “casing investigation” rather than a “casing integrity test,” amongst other issues.

- Additionally, because WEG does not use the term “casing investigation” in context anywhere else in its proposed amendments, this amendment introduces a phrase with no contextual application for how the OCD may apply or implement the “casing investigation” requirements. Thus, WEG’s amendment adding “casing investigation” introduces an unnecessary regulatory ambiguity into 19.15.25.14 and should not be adopted.

An Act

HOUSE BILL 22-1345

BY REPRESENTATIVE(S) Cutter and Bradfield, Amabile, Bacon, Bernett, Bird, Boesenecker, Duran, Exum, Froelich, Hooton, Jodeh, Kipp, Lindsay, Lontine, McCormick, Michaelson Jenet, Ricks, Sirota, Sullivan, Titone, Valdez A., Herod, Kennedy, McLachlan, Snyder, Tipper, Woodrow; also SENATOR(S) Gonzales and Lee, Bridges, Buckner, Danielson, Donovan, Fields, Hansen, Jaquez Lewis, Kolker, Moreno, Pettersen, Story, Winter, Zenzinger, Fenberg.

CONCERNING MEASURES TO INCREASE PROTECTIONS FROM PERFLUOROALKYL AND POLYFLUOROALKYL CHEMICALS.

Be it enacted by the General Assembly of the State of Colorado:

SECTION 1. In Colorado Revised Statutes, **add** part 6 to article 15 of title 25 as follows:

PART 6
PERFLUOROALKYL AND POLYFLUOROALKYL CHEMICALS

25-15-601. Short title. THE SHORT TITLE OF THIS PART 6 IS THE "PERFLUOROALKYL AND POLYFLUOROALKYL CHEMICALS CONSUMER PROTECTION ACT".

Capital letters or bold & italic numbers indicate new material added to existing law; dashes through words or numbers indicate deletions from existing law and such material is not part of the act.

NMOGA Exhibit B

25-15-602. Legislative declaration. (1) THE GENERAL ASSEMBLY HEREBY FINDS AND DECLARES THAT:

(a) CONTAMINATION OF THE SOIL AND WATER IN THE STATE FROM PFAS CHEMICALS POSES A SIGNIFICANT THREAT TO THE ENVIRONMENT OF THE STATE AND THE HEALTH OF ITS RESIDENTS;

(b) A GROWING BODY OF SCIENTIFIC RESEARCH HAS FOUND THAT EXPOSURE TO PFAS CHEMICALS MAY LEAD TO SERIOUS AND HARMFUL HEALTH EFFECTS;

(c) THE FULL EXTENT OF THE CONTAMINATION OF PFAS CHEMICALS IN THE SOIL AND WATER OF THE STATE IS NOT CURRENTLY KNOWN BUT IS ANTICIPATED TO BE WIDESPREAD AND TO REQUIRE A SIGNIFICANT EXPENDITURE OF RESOURCES TO BE IDENTIFIED AND REMEDIATED;

(d) PFAS CHEMICALS CONTINUE TO BE USED IN PRODUCTS ACROSS A VARIETY OF INDUSTRIES AND FOR MANY DIFFERENT PURPOSES;

(e) PFAS CHEMICALS ARE NOT NECESSARY IN MANY PRODUCTS AND COULD BE REPLACED WITH LESS HARMFUL CHEMICALS OR TECHNOLOGIES; AND

(f) IF THE WIDESPREAD SALE AND DISTRIBUTION OF PRODUCTS THAT CONTAIN INTENTIONALLY ADDED PFAS CHEMICALS CONTINUES IN THE STATE:

(I) THERE IS A LARGER RISK OF PFAS CHEMICALS MIGRATING INTO THE NATURAL ENVIRONMENT;

(II) RESIDENTS OF THE STATE WILL LIKELY SUFFER ADVERSE HEALTH EFFECTS FROM EXPOSURE TO PFAS CHEMICALS; AND

(III) THE STATE AND LOCAL COMMUNITIES WILL BE BURDENED WITH THE TESTING, MONITORING, AND CLEAN-UP COSTS NECESSARY TO KEEP RESIDENTS SAFE FROM EXPOSURE TO PFAS CHEMICALS.

(2) THE GENERAL ASSEMBLY THEREFORE DETERMINES AND DECLARES THAT IT IS IMPERATIVE FOR THE HEALTH AND SAFETY OF THE

STATE'S RESIDENTS TO CREATE A REGULATORY SCHEME THAT PHASES OUT THE SALE OR DISTRIBUTION OF CERTAIN PRODUCTS AND PRODUCT CATEGORIES IN THE STATE THAT CONTAIN INTENTIONALLY ADDED PFAS CHEMICALS.

25-15-603. Definitions - repeal. AS USED IN THIS PART 6, UNLESS THE CONTEXT OTHERWISE REQUIRES:

(1) "ADULT MATTRESS" MEANS A MATTRESS PRODUCT THAT IS NOT A CRIB OR A TODDLER MATTRESS.

(2) "CARPET OR RUG" MEANS A FABRIC PRODUCT MARKETED OR INTENDED FOR USE AS A FLOOR COVERING IN HOUSEHOLDS OR BUSINESSES.

(3) "CONSUMER" MEANS THE END USER OF A PRODUCT.

(4) (a) "COOKWARE" MEANS A DURABLE HOUSEWARE PRODUCT THAT IS USED IN RESIDENCES OR KITCHENS TO PREPARE, DISPENSE, OR STORE FOOD OR BEVERAGES.

(b) "COOKWARE" INCLUDES POTS, PANS, SKILLETS, GRILLS, BAKING SHEETS, BAKING MOLDS, TRAYS, BOWLS, AND COOKING UTENSILS.

(5) (a) "COSMETIC" MEANS A PRODUCT THAT IS INTENDED TO BE RUBBED OR INTRODUCED INTO; POURED, SPRINKLED, OR SPRAYED ON; OR OTHERWISE APPLIED TO THE HUMAN BODY FOR CLEANING, CLEANSING, BEAUTIFYING, PROMOTING ATTRACTIVENESS, OR ALTERING THE APPEARANCE.

(b) "COSMETIC" INCLUDES A SKIN MOISTURIZER, PERFUME, LIPSTICK, NAIL POLISH, EYE OR FACIAL MAKEUP PREPARATION, SHAMPOO, CONDITIONER, PERMANENT WAVE, HAIR DYE, AND DEODORANT.

(c) "COSMETIC" DOES NOT INCLUDE A PRODUCT THAT REQUIRES A PRESCRIPTION FOR DISTRIBUTION OR DISPENSATION.

(d) (I) "COSMETIC" DOES NOT INCLUDE HYDROFLUOROOLEFINS USED AS PROPELLANTS IN COSMETICS.

(II) THIS SUBSECTION (5)(d) IS REPEALED EFFECTIVE JANUARY 1, 2027.

(6) "DEPARTMENT" MEANS THE COLORADO DEPARTMENT OF PUBLIC HEALTH AND ENVIRONMENT.

(7) "DRILLING FLUID" MEANS A FLUID THAT IS CIRCULATED INTO THE BOREHOLE OF A WELL TO LUBRICATE AND COOL THE DRILL BIT.

(8) "EXECUTIVE DIRECTOR" MEANS THE EXECUTIVE DIRECTOR OF THE DEPARTMENT OR THE EXECUTIVE DIRECTOR'S DESIGNEE.

(9) (a) "FABRIC TREATMENT" MEANS A PRODUCT APPLIED TO FABRIC TO GIVE THE FABRIC ONE OR MORE CHARACTERISTICS, INCLUDING STAIN RESISTANCE AND WATER RESISTANCE.

(b) (I) "FABRIC TREATMENT" DOES NOT INCLUDE HYDROFLUOROOLEFINS USED AS PROPELLANTS IN FABRIC TREATMENTS.

(II) THIS SUBSECTION (9)(b) IS REPEALED EFFECTIVE JANUARY 1, 2027.

(10) "FOOD PACKAGE" OR "FOOD PACKAGING" MEANS A PACKAGE OR PACKAGING COMPONENT USED IN DIRECT CONTACT WITH FOOD AND THAT IS COMPOSED, IN SUBSTANTIAL PART, OF PAPER, PAPERBOARD, OR OTHER MATERIALS ORIGINALLY DERIVED FROM PLANT FIBERS.

(11) "HYDRAULIC FRACTURING FLUID" MEANS THE FLUID, INCLUDING THE APPLICABLE BASE FLUID AND ANY ADDITIVES, INJECTED INTO AN OIL OR GAS WELL TO PERFORM HYDRAULIC FRACTURING OPERATIONS.

(12) (a) "INTENTIONALLY ADDED PFAS CHEMICALS" MEANS PFAS CHEMICALS THAT A MANUFACTURER HAS INTENTIONALLY ADDED TO A PRODUCT AND THAT HAVE A FUNCTIONAL OR TECHNICAL EFFECT ON THE PRODUCT.

(b) "INTENTIONALLY ADDED PFAS CHEMICALS" INCLUDES PFAS CHEMICALS THAT ARE INTENTIONAL BREAKDOWN PRODUCTS OF AN ADDED CHEMICAL.

(13) (a) "JUVENILE PRODUCT" MEANS A PRODUCT DESIGNED FOR USE

BY INFANTS OR CHILDREN UNDER TWELVE YEARS OF AGE.

(b) "JUVENILE PRODUCT" INCLUDES:

(I) BASSINETS AND OTHER BEDSIDE SLEEPERS;

(II) BOOSTER SEATS, CAR SEATS, AND OTHER CHILD RESTRAINT SYSTEMS;

(III) CHANGING PADS;

(IV) CO-SLEEPERS;

(V) CRIB OR TODDLER MATTRESSES;

(VI) FLOOR PLAY MATS;

(VII) HIGHCHAIRS AND HIGHCHAIR PADS;

(VIII) INFANT BOUNCERS;

(IX) INFANT CARRIERS;

(X) INFANT OR TODDLER FOAM PILLOWS;

(XI) INFANT SEATS;

(XII) INFANT SLEEP POSITIONERS;

(XIII) INFANT SWINGS;

(XIV) INFANT TRAVEL BEDS;

(XV) INFANT WALKERS;

(XVI) NAP COTS;

(XVII) NURSING PADS AND PILLOWS;

(XVIII) PLAY MATS;

(XIX) PLAYPENS;

(XX) PLAY YARDS;

(XXI) POLYURETHANE FOAM MATS, PADS, OR PILLOWS;

(XXII) PORTABLE FOAM NAP MATS;

(XXIII) PORTABLE INFANT SLEEPERS AND HOOK-ON CHAIRS;

(XXIV) SOFT-SIDED PORTABLE CRIBS; AND

(XXV) STROLLERS.

(c) "JUVENILE PRODUCT" DOES NOT INCLUDE:

(I) ELECTRONIC PRODUCTS, INCLUDING:

(A) PERSONAL COMPUTERS AND ANY ASSOCIATED EQUIPMENT;

(B) AUDIO AND VIDEO EQUIPMENT;

(C) CALCULATORS;

(D) WIRELESS PHONES;

(E) GAMING CONSOLES;

(F) HANDHELD DEVICES INCORPORATING A VIDEO SCREEN; AND

(G) ANY ASSOCIATED PERIPHERAL DEVICE SUCH AS A MOUSE, KEYBOARD, POWER SUPPLY UNIT, OR POWER CORD;

(II) AN INTERNAL COMPONENT OF A JUVENILE PRODUCT THAT WOULD NOT COME INTO DIRECT CONTACT WITH A CHILD'S SKIN OR MOUTH DURING REASONABLY FORESEEABLE USE AND ABUSE OF THE PRODUCT; OR

(III) ADULT MATTRESSES.

(14) (a) "MANUFACTURER" MEANS THE PERSON THAT

MANUFACTURES OR ASSEMBLES A PRODUCT OR WHOSE BRAND NAME IS AFFIXED TO A PRODUCT.

(b) "MANUFACTURER" INCLUDES, IF A PRODUCT IS IMPORTED INTO THE UNITED STATES AND THE MANUFACTURER DOES NOT HAVE A PRESENCE IN THE UNITED STATES, THE IMPORTER OR FIRST DOMESTIC DISTRIBUTOR OF THE PRODUCT.

(15) "OIL AND GAS OPERATIONS" HAS THE MEANING SET FORTH IN SECTION 34-60-103 (6.5).

(16) "OIL AND GAS PRODUCTS" MEANS HYDRAULIC FRACTURING FLUIDS, DRILLING FLUIDS, AND PROPPANTS.

(17) "PACKAGE" MEANS MATERIAL THAT IS INTENDED OR USED TO CONTAIN, PROTECT, HANDLE, DELIVER, OR PRESENT A PRODUCT.

(18) "PACKAGING COMPONENT" MEANS AN INDIVIDUAL PART OF A PACKAGE, INCLUDING INTERIOR OR EXTERIOR BLOCKING, BRACING, CUSHIONING, WEATHERPROOFING, EXTERIOR STRAPPING, COATINGS, CLOSURES, INKS, AND LABELS.

(19) "PFAS CHEMICALS" HAS THE MEANING SET FORTH IN SECTION 25-5-1302 (7).

(20) (a) "PRODUCT" MEANS AN ITEM THAT IS MANUFACTURED, ASSEMBLED, OR OTHERWISE PREPARED FOR SALE OR DISTRIBUTION TO CONSUMERS AND THAT IS SOLD OR DISTRIBUTED FOR PERSONAL, RESIDENTIAL, COMMERCIAL, OR INDUSTRIAL USE, INCLUDING FOR USE IN MAKING OTHER PRODUCTS.

(b) "PRODUCT" INCLUDES ANY PRODUCT COMPONENTS.

(c) "PRODUCT" DOES NOT INCLUDE:

(I) DRUGS, MEDICAL DEVICES, BIOLOGICS, OR DIAGNOSTICS APPROVED OR AUTHORIZED BY THE FEDERAL FOOD AND DRUG ADMINISTRATION OR THE FEDERAL DEPARTMENT OF AGRICULTURE; OR

(II) VETERINARY PESTICIDE PRODUCTS APPROVED BY THE FEDERAL

ENVIRONMENTAL PROTECTION AGENCY FOR USE IN ANIMALS; OR

(III) PACKAGING USED FOR THE PRODUCTS DESCRIBED IN SUBSECTIONS (20)(c)(I) AND (20)(c)(II) OF THIS SECTION.

(d) "PRODUCT" DOES NOT INCLUDE A USED PRODUCT OFFERED FOR SALE OR RESALE.

(21) "PRODUCT CATEGORY" MEANS A CLASS OR DIVISION OF PRODUCTS THAT SHARE RELATED CHARACTERISTICS.

(22) "PRODUCT COMPONENT" MEANS AN IDENTIFIABLE COMPONENT OF A PRODUCT, REGARDLESS OF WHETHER THE MANUFACTURER OF THE PRODUCT IS THE MANUFACTURER OF THE COMPONENT.

(23) "PROPPANTS" MEANS MATERIALS THAT ARE INSERTED OR INJECTED INTO AN UNDERGROUND GEOLOGIC FORMATION DURING OIL AND GAS OPERATIONS IN ORDER TO PREVENT FRACTURES FROM CLOSING.

(24) (a) "TEXTILE" MEANS ANY PRODUCT MADE IN WHOLE OR IN PART FROM A NATURAL OR SYNTHETIC FIBER, YARN, OR FABRIC.

(b) "TEXTILE" INCLUDES LEATHER, COTTON, SILK, JUTE, HEMP, WOOL, NYLON, AND POLYESTER.

(c) "TEXTILE" DOES NOT INCLUDE TEXTILES USED IN MEDICAL, PROFESSIONAL, OR INDUSTRIAL SETTINGS.

(25) (a) "TEXTILE FURNISHINGS" MEANS TEXTILES OF A TYPE CUSTOMARILY USED IN HOUSEHOLDS AND BUSINESSES, INCLUDING DRAPERIES, FLOOR COVERINGS, FURNISHINGS, BEDDING, TOWELS, AND TABLECLOTHS.

(b) "TEXTILE FURNISHINGS" DOES NOT INCLUDE TEXTILE FURNISHINGS USED IN MEDICAL, PROFESSIONAL, OR INDUSTRIAL SETTINGS.

(26) "UPHOLSTERED FURNITURE" MEANS ANY ARTICLE OF FURNITURE THAT IS:

(a) DESIGNED FOR SITTING, RESTING, OR RECLINING; AND

(b) WHOLLY OR PARTIALLY STUFFED WITH FILLING MATERIAL.

25-15-604. Prohibition on the sale or distribution of certain consumer products that contain intentionally added PFAS chemicals - product label requirements for cookware. (1) ON AND AFTER JANUARY 1, 2024, A PERSON SHALL NOT SELL, OFFER FOR SALE, DISTRIBUTE FOR SALE, OR DISTRIBUTE FOR USE IN THE STATE ANY PRODUCT IN ANY OF THE FOLLOWING PRODUCT CATEGORIES IF THE PRODUCT CONTAINS INTENTIONALLY ADDED PFAS CHEMICALS:

(a) CARPETS OR RUGS;

(b) FABRIC TREATMENTS;

(c) FOOD PACKAGING;

(d) JUVENILE PRODUCTS; AND

(e) OIL AND GAS PRODUCTS.

(2) (a) ON AND AFTER JANUARY 1, 2024, A MANUFACTURER OF COOKWARE SOLD IN THE STATE THAT CONTAINS INTENTIONALLY ADDED PFAS CHEMICALS IN THE HANDLE OF THE PRODUCT OR IN ANY PRODUCT SURFACE THAT COMES INTO CONTACT WITH FOOD, FOODSTUFFS, OR BEVERAGES SHALL LIST THE PRESENCE OF PFAS CHEMICALS ON THE PRODUCT LABEL AND SHALL INCLUDE ON THE PRODUCT LABEL A STATEMENT, IN BOTH ENGLISH AND SPANISH, THAT READS: "FOR MORE INFORMATION ABOUT PFAS CHEMICALS IN THIS PRODUCT, VISIT" FOLLOWED BY BOTH OF THE FOLLOWING:

(I) AN INTERNET WEBSITE ADDRESS FOR A WEB PAGE THAT PROVIDES INFORMATION ABOUT WHY THE PFAS CHEMICALS ARE INTENTIONALLY ADDED; AND

(II) A QUICK RESPONSE (QR) CODE OR OTHER MACHINE-READABLE CODE, CONSISTING OF AN ARRAY OF SQUARES, USED FOR STORING AN INTERNET WEBSITE FOR A WEB PAGE THAT PROVIDES INFORMATION ABOUT WHY THE PFAS CHEMICALS ARE INTENTIONALLY ADDED.

(b) A MANUFACTURER OF COOKWARE SOLD IN THE STATE SHALL

ENSURE THAT THE STATEMENT REQUIRED ON THE PRODUCT LABEL BY SUBSECTION (2)(a) OF THIS SECTION IS VISIBLE AND LEGIBLE TO THE CONSUMER, INCLUDING ON THE PRODUCT LISTING FOR ONLINE SALES.

(c) COOKWARE THAT MEETS BOTH OF THE FOLLOWING REQUIREMENTS IS EXEMPT FROM THE REQUIREMENT OF THIS SUBSECTION (2):

(I) THE SURFACE AREA OF THE COOKWARE CANNOT FIT A PRODUCT LABEL OF AT LEAST TWO SQUARE INCHES; AND

(II) THE COOKWARE DOES NOT HAVE EITHER OF THE FOLLOWING:

(A) AN EXTERIOR CONTAINER OR WRAPPER ON WHICH A PRODUCT LABEL CAN APPEAR OR BE AFFIXED; AND

(B) A TAG OR OTHER ATTACHMENT WITH INFORMATION ABOUT THE PRODUCT ATTACHED TO THE COOKWARE.

(d) A MANUFACTURER OF COOKWARE SOLD IN THE STATE SHALL ENSURE THAT THE STATEMENT OTHERWISE REQUIRED ON THE PRODUCT LABEL BY SUBSECTION (2)(a) OF THIS SECTION IS INCLUDED ON THE PRODUCT LISTING FOR ONLINE SALES PURSUANT TO SUBSECTION (2)(b) OF THIS SECTION.

(e) ON AND AFTER JANUARY 1, 2024, A MANUFACTURER SHALL NOT MAKE A CLAIM, ON THE COOKWARE PACKAGE, THAT THE COOKWARE IS FREE OF ANY PFAS CHEMICALS UNLESS NO INDIVIDUAL PFAS CHEMICAL IS INTENTIONALLY ADDED TO THE COOKWARE.

(f) COOKWARE THAT CONTAINS ONE OR MORE INTENTIONALLY ADDED PFAS CHEMICALS IN THE HANDLE OF THE PRODUCT OR IN ANY PRODUCT SURFACE THAT COMES INTO CONTACT WITH FOOD, FOODSTUFFS, OR BEVERAGES SHALL NOT BE SOLD, OFFERED FOR SALE, OR DISTRIBUTED IN THE STATE UNLESS THE COOKWARE AND THE MANUFACTURER OF THE COOKWARE COMPLY WITH THIS PART 6.

(3) ON AND AFTER JANUARY 1, 2025, A PERSON SHALL NOT SELL, OFFER FOR SALE, DISTRIBUTE FOR SALE, OR DISTRIBUTE FOR USE THE FOLLOWING PRODUCTS THAT CONTAIN INTENTIONALLY ADDED PFAS CHEMICALS:

(a) COSMETICS;

(b) INDOOR TEXTILE FURNISHINGS; AND

(c) INDOOR UPHOLSTERED FURNITURE.

(4) ON AND AFTER JANUARY 1, 2027, A PERSON SHALL NOT SELL, OFFER FOR SALE, DISTRIBUTE FOR SALE, OR DISTRIBUTE FOR USE THE FOLLOWING PRODUCTS THAT CONTAIN INTENTIONALLY ADDED PFAS CHEMICALS:

(a) OUTDOOR TEXTILE FURNISHINGS; AND

(b) OUTDOOR UPHOLSTERED FURNITURE.

SECTION 2. In Colorado Revised Statutes, 24-103-904, **amend** (1) as follows:

24-103-904. Purchasing preference for environmentally preferable products - definitions. (1) As used in this section, unless the context otherwise requires:

(a) "Environmentally preferable products" means products, INCLUDING PRODUCTS THAT DO NOT CONTAIN INTENTIONALLY ADDED PFAS CHEMICALS, that have a lesser or reduced adverse effect on human health and the environment when compared with competing products that serve the same purpose. The product comparison may consider such factors as the availability of any raw materials used in the product being purchased and the availability, use, production, safe operation, maintenance, packaging, distribution, disposal, or recyclability of the product being purchased.

(b) "INTENTIONALLY ADDED PFAS CHEMICALS" HAS THE MEANING SET FORTH IN SECTION 25-15-603 (12).

SECTION 3. In Colorado Revised Statutes, 25-5-1302, **add** (1.5), (3.6), (5.8), (7.5), (9), and (10) as follows:

25-5-1302. Definitions. As used in this part 13, unless the context otherwise requires:

(1.5) "CLASS B FIRE" MEANS A FIRE INVOLVING FLAMMABLE LIQUIDS OR GASES, INCLUDING PETROLEUM, PAINT, ALCOHOL, SOLVENT, OIL, AND TAR.

(3.6) "EXECUTIVE DIRECTOR" MEANS THE EXECUTIVE DIRECTOR OF THE DEPARTMENT OR THE EXECUTIVE DIRECTOR'S DESIGNEE.

(5.8) "INTENTIONALLY ADDED PFAS CHEMICALS" HAS THE MEANING SET FORTH IN SECTION 25-15-603 (12).

(7.5) "RELEASE" MEANS ANY SPILLING, LEAKING, PUMPING, POURING, EMPTYING, DISCHARGING, INJECTING, ESCAPING, LEACHING, DUMPING, OR DISPOSING OF A CHEMICAL INTO THE ENVIRONMENT.

(9) "TERMINAL" MEANS A FACILITY THAT ENGAGES IN THE WHOLESALE DISTRIBUTION OF CRUDE PETROLEUM AND PETROLEUM PRODUCTS, INCLUDING LIQUIFIED PETROLEUM GAS FROM BULK LIQUID STORAGE FACILITIES.

(10) "WATER QUALITY SPILLS HOTLINE" MEANS THE PHONE SYSTEM CREATED AND MAINTAINED BY THE DEPARTMENT FOR THE REPORTING OF SPILLS OR DISCHARGES INTO STATE WATERS TO THE DEPARTMENT.

SECTION 4. In Colorado Revised Statutes, **add** 25-5-1303.5 as follows:

25-5-1303.5. Restriction on use of certain firefighting foams. (1) BEGINNING JANUARY 1, 2024, A PERSON THAT USES CLASS B FIREFIGHTING FOAM CONTAINING INTENTIONALLY ADDED PFAS CHEMICALS SHALL:

(a) NOT ALLOW A RELEASE OF THE CLASS B FIREFIGHTING FOAM;

(b) FULLY CONTAIN THE CLASS B FIREFIGHTING FOAM BY IMPLEMENTING APPROPRIATE CONTAINMENT MEASURES, WHICH MAY INCLUDE BUNDS AND PONDS, THAT:

(I) ARE CONTROLLED;

(II) ARE IMPERVIOUS TO PFAS CHEMICALS; AND

(III) DO NOT ALLOW THE CLASS B FIREFIGHTING FOAM OR ANY ASSOCIATED FIREWATER, WASTEWATER, RUNOFF, OR OTHER WASTE TO BE RELEASED;

(c) SAFELY STORE ALL CLASS B FIREFIGHTING FOAM AND ANY ASSOCIATED FIREWATER, WASTEWATER, RUNOFF, AND OTHER WASTE IN A WAY THAT PREVENTS THEIR RELEASE UNTIL THE FEDERAL ENVIRONMENTAL PROTECTION AGENCY HAS PUBLISHED GUIDANCE ON THE PROPER DISPOSAL AND DESTRUCTION METHODS FOR PFAS CHEMICALS. AFTER THE FEDERAL ENVIRONMENTAL PROTECTION AGENCY HAS PUBLISHED GUIDANCE ON THE PROPER DISPOSAL AND DESTRUCTION METHODS FOR PFAS CHEMICALS, THE PERSON THAT USES THE CLASS B FIREFIGHTING FOAM CONTAINING INTENTIONALLY ADDED PFAS CHEMICALS SHALL DISPOSE OF AND DESTROY THE CLASS B FIREFIGHTING FOAM IN ACCORDANCE WITH SUCH GUIDANCE.

(d) IF THERE IS A RELEASE OF THE CLASS B FIREFIGHTING FOAM OR ANY ASSOCIATED FIREWATER, WASTEWATER, RUNOFF, OR OTHER WASTE, REPORT THE FOLLOWING INFORMATION TO THE WATER QUALITY SPILLS HOTLINE WITHIN TWENTY-FOUR HOURS AFTER ITS RELEASE:

(I) THE TRADE NAME AND PRODUCT NAME OF THE CLASS B FIREFIGHTING FOAM;

(II) THE QUANTITY OF CLASS B FIREFIGHTING FOAM USED THAT CONTAINS INTENTIONALLY ADDED PFAS CHEMICALS;

(III) THE AMOUNT AND TYPE OF PFAS CHEMICALS IN THE CLASS B FIREFIGHTING FOAM; AND

(IV) THE AMOUNT OF CLASS B FIREFIGHTING FOAM OR ANY ASSOCIATED FIREWATER, WASTEWATER, RUNOFF, AND OTHER WASTE THAT IS RELEASED; AND

(e) DOCUMENT ANY MEASURES UNDERTAKEN PURSUANT TO THE REQUIREMENTS OF THIS SECTION. IN INVESTIGATING COMPLIANCE WITH THE REQUIREMENTS OF THIS SECTION, THE ATTORNEY GENERAL MAY REQUEST THAT THE PERSON PROVIDE THE DOCUMENTATION CREATED PURSUANT TO THE REQUIREMENTS OF THIS SUBSECTION (1)(e) TO THE ATTORNEY GENERAL.

(2) BEGINNING JANUARY 1, 2024, A PERSON THAT USES CLASS B

FIREFIGHTING FOAM THAT CONTAINS INTENTIONALLY ADDED PFAS CHEMICALS MUST REPORT THE USE OF THE CLASS B FIREFIGHTING FOAM TO THE WATER QUALITY SPILLS HOTLINE WITHIN TWENTY-FOUR HOURS AFTER ITS USE.

(3) (a) EXCEPT AS PROVIDED IN SUBSECTION (3)(b) OF THIS SECTION, THE RESTRICTIONS AND REQUIREMENTS IN SUBSECTIONS (1) AND (2) OF THIS SECTION DO NOT APPLY TO THE USE OF CLASS B FIREFIGHTING FOAM WHERE THE INCLUSION OF PFAS CHEMICALS IS REQUIRED OR AUTHORIZED BY FEDERAL LAW, INCLUDING 14 CFR 139, OR IMPLEMENTED IN ACCORDANCE WITH FEDERAL AVIATION ADMINISTRATION GUIDANCE, OR OTHERWISE REQUIRED FOR A MILITARY PURPOSE.

(b) IF THE EXECUTIVE DIRECTOR DETERMINES BY RULE THAT THE LAWS, GUIDANCE, OR REQUIREMENTS DESCRIBED IN SUBSECTION (3)(a) OF THIS SECTION NO LONGER APPLY TO A PARTICULAR INDUSTRY OR SECTOR, THE EXECUTIVE DIRECTOR SHALL PROVIDE NOTICE ON THE DEPARTMENT'S WEBSITE OF THIS DETERMINATION AND SHALL PROMULGATE RULES PROHIBITING USERS OF CLASS B FIREFIGHTING FOAM WITHIN THAT INDUSTRY OR SECTOR FROM USING CLASS B FIREFIGHTING FOAM IN VIOLATION OF THIS SECTION, WHICH RULES SHALL APPLY NO SOONER THAN TWO YEARS AFTER THE EXECUTIVE DIRECTOR'S DETERMINATION.

SECTION 5. In Colorado Revised Statutes, **amend** 25-5-1307 as follows:

25-5-1307. Civil penalty. (1) A manufacturer or a person who violates ~~the provisions of~~ this part 13 is subject to a civil penalty not to exceed five thousand dollars for each violation in the case of a first offense. A manufacturer or a person who violates this part 13 repeatedly is subject to a civil penalty not to exceed ten thousand dollars for each repeat offense. Penalties collected under this part 13 must be deposited in the local firefighter safety and disease prevention fund created in section 24-33.5-1231.

(2) THE ATTORNEY GENERAL HAS THE AUTHORITY TO ENFORCE THIS PART 13 AND TO CONDUCT CIVIL INVESTIGATIONS AND BRING CIVIL ACTIONS FOR VIOLATIONS OF THIS PART 13.

SECTION 6. In Colorado Revised Statutes, 25-5-1309, **amend** (1) introductory portion as follows:

25-5-1309. Restriction on the use of certain firefighting foam at certain airports - definitions. (1) Beginning January 1, ~~2023~~ 2024, the use of class B firefighting foam that contains intentionally added perfluoroalkyl and polyfluoroalkyl substances shall be prohibited at structures used for the storage or maintenance of aircraft where the structure is located in an airport that:

SECTION 7. Safety clause. The general assembly hereby finds, determines, and declares that this act is necessary for the immediate preservation of the public peace, health, or safety.

Alec Garnett
SPEAKER OF THE HOUSE
OF REPRESENTATIVES

Steve Fenberg
PRESIDENT OF
THE SENATE

Robin R. Jones

Robin Jones
CHIEF CLERK OF THE HOUSE
OF REPRESENTATIVES

Cindi L. Markwell

Cindi L. Markwell
SECRETARY OF
THE SENATE

APPROVED June 3, 2022 at 9:05am
(Date and Time)

Jared S. Polis
GOVERNOR OF THE STATE OF COLORADO

An Act

HOUSE BILL 22-1348

BY REPRESENTATIVE(S) Froelich and Caraveo, Amabile, Bacon, Bernett, Cutter, Duran, Gray, Hooton, Jodeh, Kennedy, Kipp, Lindsay, Lontine, Sirota, Bird, Boesenecker, Gonzales-Gutierrez, McCormick, Ricks, Titone, Valdez A., Weissman, Benavidez, Herod, Snyder, Sullivan, Woodrow;
also SENATOR(S) Winter, Buckner, Donovan, Ginal, Gonzales, Hansen, Jaquez Lewis, Lee, Moreno, Pettersen, Story, Zenzinger, Fenberg.

CONCERNING ENHANCED OVERSIGHT OF THE CHEMICALS USED IN OIL AND GAS PRODUCTION, AND, IN CONNECTION THEREWITH, MAKING AN APPROPRIATION.

Be it enacted by the General Assembly of the State of Colorado:

SECTION 1. Legislative declaration. (1) The general assembly hereby finds and declares that:

(a) There are tens of thousands of active oil and gas wells in Colorado;

(b) Many different types of products that contain chemical additives are used by operators during the drilling and stimulation of these wells to

---

Capital letters or bold & italic numbers indicate new material added to existing law; dashes through words or numbers indicate deletions from existing law and such material is not part of the act.

NMOGA Exhibit C

break up the subsurface and extract oil and gas from the ground;

(c) While water and sand can make up the vast majority of these products, the amount of chemical additives injected into a well can add up to tens of thousands of gallons because of the amount of these products that are used during the course of an oil and gas operation;

(d) When these chemical additives are injected into a well, there is a high risk of contamination to nearby groundwater or surface water; and

(e) Some chemicals used in chemical products, such as perfluoroalkyl and polyfluoroalkyl chemicals and biocides, have high aquatic toxicity and can be incredibly harmful to human health and the environment.

(2) The general assembly further finds and declares that:

(a) Even though exposure to these chemical additives poses a danger to public health and the environment, scientists, state and local regulators, and the public lack full access to information about the chemical additives used in oil and gas production in the state;

(b) While Colorado requires the reporting of certain chemical information for products that are used in hydraulic fracturing (fracking) operations for input into a third-party database, there are broad exemptions allowed for chemical information that is deemed proprietary or confidential by the operator or supplier of a product;

(c) In recent years, thousands of operators who conduct fracking operations have used trade secrecy claims to avoid disclosing information about the chemicals that they use in their operations;

(d) Operators and suppliers of the products often do not have knowledge of the chemical information that they are required to report to the state;

(e) As a result of the amount of trade secrecy claims and the operators' and suppliers' lack of knowledge of specific chemical information, information about the chemical additives that are used in fracking operations in the state is vastly underreported;

(f) Greater transparency regarding chemical use in oil and gas production is urgently needed and can be achieved by:

(I) Requiring manufacturers and disclosers, rather than operators, to disclose information about chemicals that are used in oil and gas production in the state;

(II) Requiring the Colorado oil and gas conservation commission to gather the chemical information so that the disclosure of specific chemical information can be separated from the trade name of a product, which will thereby protect any proprietary information; and

(III) Ensuring that operators disclose chemical information to the state, local governments, and communities in close proximity to operations after the operations have commenced; and

(g) A full inventory of the chemicals used in oil and gas production will:

(I) Assist state agencies, local governments, health-care professionals, public health officials, and scientists in determining if highly hazardous chemicals are being used in oil and gas production; and

(II) Encourage the disclosers and users of products that contain highly hazardous chemicals to use less toxic alternatives in future products and oil and gas operations.

(3) Therefore the general assembly determines and declares that the state should enact a regulatory scheme that provides full disclosure of the chemicals that are being deposited into the environment through oil and gas production because:

(a) Coloradans have the right to know what chemicals are being deposited into the environment where they live, work, and recreate; and

(b) State and local governments and regulators need this chemical information to adequately protect the people, water systems, wildlife, and environment of Colorado.

SECTION 2. In Colorado Revised Statutes, **add** 34-60-132 as follows:

34-60-132. Disclosure of chemicals used in downhole oil and gas operations - chemical disclosure lists - community notification - reports - definitions - rules - repeal. (1) AS USED IN THIS SECTION, UNLESS THE CONTEXT OTHERWISE REQUIRES:

(a) (I) "ADDITIVE" MEANS A CHEMICAL OR COMBINATION OF CHEMICALS ADDED TO A BASE FLUID FOR USE IN A HYDRAULIC FRACTURING TREATMENT.

(II) "ADDITIVE" INCLUDES PROPPANTS.

(b) "BASE FLUID" MEANS THE CONTINUOUS PHASE FLUID TYPE, SUCH AS WATER, USED IN A HYDRAULIC FRACTURING TREATMENT.

(c) "CHEMICAL" MEANS ANY ELEMENT, CHEMICAL COMPOUND, OR MIXTURE OF ELEMENTS OR CHEMICAL COMPOUNDS THAT HAS A SPECIFIC NAME OR IDENTITY, INCLUDING A CHEMICAL ABSTRACTS SERVICE NUMBER.

(d) "CHEMICAL ABSTRACTS SERVICE NUMBER" MEANS THE UNIQUE NUMERICAL IDENTIFIER ASSIGNED BY THE CHEMICAL ABSTRACTS SERVICE TO A CHEMICAL.

(e) "CHEMICAL DISCLOSURE INFORMATION" MEANS THE INFORMATION DISCLOSED TO THE COMMISSION UNDER SUBSECTIONS (2)(a)(I) AND (3)(a)(I) OF THIS SECTION.

(f) "CHEMICAL DISCLOSURE LIST" MEANS A LIST OF CHEMICALS USED IN DOWNHOLE OPERATIONS AT A WELL SITE.

(g) "CHEMICAL DISCLOSURE WEBSITE" MEANS A WEBSITE THAT IS CAPABLE OF DISPLAYING CHEMICAL DISCLOSURE LISTS AND CAN BE ACCESSED BY THE PUBLIC.

(h) (I) "CHEMICAL PRODUCT" MEANS ANY PRODUCT THAT CONSISTS OF ONE OR MORE CHEMICALS AND IS SOLD OR DISTRIBUTED FOR USE IN DOWNHOLE OPERATIONS IN THE STATE.

(II) "CHEMICAL PRODUCT" INCLUDES ADDITIVES, BASE FLUIDS, AND

HYDRAULIC FRACTURING FLUIDS.

(III) "CHEMICAL PRODUCT" DOES NOT INCLUDE THE STRUCTURAL AND MECHANICAL COMPONENTS OF A WELL SITE WHERE DOWNHOLE OPERATIONS ARE BEING CONDUCTED.

(i) (I) "DIRECT VENDOR" MEANS ANY DISTRIBUTOR, SUPPLIER, OR OTHER ENTITY THAT SELLS OR SUPPLIES ONE OR MORE CHEMICAL PRODUCTS DIRECTLY TO AN OPERATOR OR SERVICE PROVIDER FOR USE AT A WELL SITE.

(II) "DIRECT VENDOR" DOES NOT INCLUDE ENTITIES THAT MANUFACTURE, PRODUCE, OR FORMULATE CHEMICAL PRODUCTS FOR FURTHER MANUFACTURE, FORMULATION, SALE, OR DISTRIBUTION BY THIRD PARTIES PRIOR TO BEING SUPPLIED DIRECTLY TO OPERATORS OR SERVICE PROVIDERS.

(j) "DISCLOSER" MEANS AN OPERATOR, ANY SERVICE PROVIDER USING ONE OR MORE CHEMICAL PRODUCTS IN THE COURSE OF DOWNHOLE OPERATIONS, AND ANY DIRECT VENDOR THAT PROVIDES ONE OR MORE CHEMICAL PRODUCTS DIRECTLY TO THE OPERATOR OR SERVICE PROVIDER FOR USE AT A WELL SITE.

(k) "DIVISION" MEANS THE DIVISION OF PARKS AND WILDLIFE IN THE DEPARTMENT OF NATURAL RESOURCES.

(l) "DOWNHOLE OPERATIONS" MEANS OIL AND GAS PRODUCTION OPERATIONS THAT ARE CONDUCTED UNDERGROUND.

(m) "HEALTH-CARE PROFESSIONAL" MEANS A PHYSICIAN, PHYSICIAN ASSISTANT, NURSE PRACTITIONER, REGISTERED NURSE, OR EMERGENCY MEDICAL SERVICE PROVIDER LICENSED OR CERTIFIED BY THE STATE.

(n) "HIGH-PRIORITY HABITAT" MEANS HABITAT AREAS IDENTIFIED BY THE DIVISION WHERE MEASURES TO AVOID, MINIMIZE, AND MITIGATE ADVERSE IMPACTS TO WILDLIFE HAVE BEEN IDENTIFIED TO PROTECT BREEDING, NESTING, FORAGING, MIGRATING, OR OTHER USES BY WILDLIFE.

(o) "HYDRAULIC FRACTURING FLUID" MEANS THE FLUID, INCLUDING ANY BASE FLUID AND ADDITIVES, USED TO PERFORM A HYDRAULIC FRACTURING TREATMENT.

(p) "HYDRAULIC FRACTURING TREATMENT" MEANS ALL STAGES OF THE TREATMENT OF A WELL BY THE APPLICATION OF HYDRAULIC FRACTURING FLUID UNDER PRESSURE, WHICH TREATMENT IS EXPRESSLY DESIGNED TO INITIATE OR PROPAGATE FRACTURES IN AN UNDERGROUND GEOLOGIC FORMATION TO ENHANCE THE PRODUCTION OF OIL AND GAS.

(q) "MANUFACTURER" MEANS A PERSON OR ENTITY THAT MAKES, ASSEMBLES, OR OTHERWISE GENERATES A CHEMICAL PRODUCT OR WHOSE TRADE NAME IS AFFIXED TO A CHEMICAL PRODUCT.

(r) "PERFLUOROALKYL AND POLYFLUOROALKYL SUBSTANCES" OR "PFAS CHEMICALS" HAS THE MEANING SET FORTH IN SECTION 25-5-1302 (7).

(s) "PROPPANTS" MEANS MATERIALS INSERTED OR INJECTED INTO AN UNDERGROUND GEOLOGIC FORMATION DURING A HYDRAULIC FRACTURING TREATMENT THAT ARE INTENDED TO PREVENT FRACTURES FROM CLOSING.

(t) "PUBLIC WATER SYSTEMS" HAS THE MEANING SET FORTH IN SECTION 25-1.5-201 (1).

(u) "TRADE SECRET" HAS THE MEANING SET FORTH IN SECTION 7-74-102 (4).

(v) "TYPE III AQUIFER" MEANS AN AQUIFER THAT CONSISTS OF UNCONSOLIDATED GEOLOGIC MATERIAL, INCLUDING ALLUVIAL, COLLUVIAL, OR OTHER CONSOLIDATED MATERIALS.

(w) "WELL SITE" MEANS THE AREA THAT IS DIRECTLY DISTURBED DURING OIL AND GAS OPERATIONS.

(2) **Discloser chemical disclosure information and declaration.** (a) ON AND AFTER JULY 31, 2023, AND SUBJECT TO SUBSECTION (2)(b) OF THIS SECTION, A DISCLOSER THAT SELLS OR DISTRIBUTES A CHEMICAL PRODUCT FOR USE IN DOWNHOLE OPERATIONS IN THE STATE OR THAT USES A CHEMICAL PRODUCT IN DOWNHOLE OPERATIONS IN THE STATE MUST:

(I) DISCLOSE TO THE COMMISSION:

(A) THE TRADE NAME OF THE CHEMICAL PRODUCT; AND

(B) A LIST OF THE NAMES AND CHEMICAL ABSTRACTS SERVICE NUMBERS OF EACH CHEMICAL USED IN THE CHEMICAL PRODUCT; AND

(C) IF A DISCLOSER BELIEVES THAT A CHEMICAL CONSTITUENT OF A CHEMICAL PRODUCT IS A TRADE SECRET OR IS PROPRIETARY INFORMATION, NEVERTHELESS DISCLOSE THE CHEMICAL CONSTITUENT; AND

(II) PROVIDE A WRITTEN DECLARATION TO THE COMMISSION THAT THE CHEMICAL PRODUCT CONTAINS NO INTENTIONALLY ADDED PFAS CHEMICALS.

(b) (I) (A) FOR DISCLOSERS THAT WERE ALREADY SELLING OR DISTRIBUTING A CHEMICAL PRODUCT FOR USE IN DOWNHOLE OPERATIONS IN THE STATE BEFORE JULY 31, 2023, OR THAT WERE USING THE CHEMICAL PRODUCT BEFORE JULY 31, 2023, THE INFORMATION AND DECLARATION REQUIRED TO BE PROVIDED PURSUANT TO SUBSECTION (2)(a) OF THIS SECTION MUST BE PROVIDED TO THE COMMISSION AT LEAST THIRTY DAYS BEFORE JULY 31, 2023.

(B) THIS SUBSECTION (2)(b)(I) IS REPEALED, EFFECTIVE JULY 1, 2024.

(II) FOR DISCLOSERS THAT BEGIN TO SELL, DISTRIBUTE, OR USE A CHEMICAL PRODUCT FOR USE IN DOWNHOLE OPERATIONS IN THE STATE ON OR AFTER JULY 31, 2023, THE INFORMATION AND DECLARATION REQUIRED TO BE PROVIDED PURSUANT TO SUBSECTION (2)(a) OF THIS SECTION MUST BE PROVIDED TO THE COMMISSION AT LEAST THIRTY DAYS BEFORE THE DISCLOSER BEGINS SELLING, DISTRIBUTING, OR USING THE CHEMICAL PRODUCT.

(c) THE COMMISSION SHALL ENSURE THAT THE INFORMATION AND DECLARATION REQUIRED TO BE PROVIDED UNDER SUBSECTION (2)(a) OF THIS SECTION IS PROVIDED TO THE COMMISSION.

(d) IF A MANUFACTURER DOES NOT PROVIDE THE INFORMATION DESCRIBED IN SUBSECTION (2)(a)(I) OF THIS SECTION FOR A CHEMICAL PRODUCT THAT IT SELLS OR DISTRIBUTES FOR USE IN DOWNHOLE OPERATIONS IN THE STATE TO A DISCLOSER UPON THE REQUEST OF THE DISCLOSER OR THE COMMISSION, THE MANUFACTURER MUST PROVIDE THE COMMISSION WITH A TRADE SECRET FORM OF ENTITLEMENT, AS DETERMINED BY THE COMMISSION

BY RULE, FOR THE CHEMICAL PRODUCT. AT A MINIMUM, THE MANUFACTURER MUST INCLUDE IN THE TRADE SECRET FORM OF ENTITLEMENT FOR THE CHEMICAL PRODUCT:

(I) THE NAME OF EACH CHEMICAL USED IN THE CHEMICAL PRODUCT; AND

(II) THE CHEMICAL ABSTRACTS SERVICE NUMBER OF EACH CHEMICAL USED IN THE CHEMICAL PRODUCT.

(e) IF, AFTER MAKING A REQUEST TO THE MANUFACTURER OF THE CHEMICAL PRODUCT PURSUANT TO SUBSECTION (2)(d) OF THIS SECTION, A DISCLOSER IS UNABLE TO DISCLOSE THE INFORMATION DESCRIBED IN SUBSECTION (2)(a)(I) OF THIS SECTION, THE DISCLOSER SHALL DISCLOSE TO THE COMMISSION:

(I) THE NAME OF THE CHEMICAL PRODUCT'S MANUFACTURER;

(II) THE CHEMICAL PRODUCT'S TRADE NAME;

(III) THE AMOUNT OR WEIGHT OF THE CHEMICAL PRODUCT; AND

(IV) A SAFETY DATA SHEET FOR THE CHEMICAL PRODUCT, IF IT IS AVAILABLE FOR DISCLOSURE BY THE DISCLOSER AND PROVIDES THE INFORMATION DESCRIBED IN SUBSECTION (2)(a)(I) OF THIS SECTION.

(f) IN THE EVENT THAT THE DISCLOSER IS UNABLE TO DISCLOSE THE INFORMATION DESCRIBED IN SUBSECTION (2)(a)(I) OF THIS SECTION, THE COMMISSION SHALL OBTAIN THE INFORMATION DESCRIBED IN SUBSECTION (2)(a)(I) OF THIS SECTION FROM THE MANUFACTURER.

(3) **Operator chemical disclosure information - declaration.** (a) ON AND AFTER JULY 31, 2023, AND SUBJECT TO SUBSECTION (3)(b) OF THIS SECTION, AN OPERATOR OF DOWNHOLE OPERATIONS USING A CHEMICAL PRODUCT MUST:

(I) DISCLOSE TO THE COMMISSION:

(A) THE DATE OF COMMENCEMENT OF DOWNHOLE OPERATIONS;

(B) THE COUNTY OF THE WELL SITE WHERE DOWNHOLE OPERATIONS ARE BEING OR WILL BE CONDUCTED;

(C) THE UNIQUE NUMERICAL IDENTIFIER ASSIGNED BY THE AMERICAN PETROLEUM INSTITUTE TO THE WELL WHERE DOWNHOLE OPERATIONS ARE BEING OR WILL BE CONDUCTED AND THE US WELL NUMBER ASSIGNED TO THE WELL WHERE DOWNHOLE OPERATIONS ARE BEING OR WILL BE CONDUCTED; AND

(D) THE TRADE NAMES AND QUANTITIES OF ANY CHEMICAL PRODUCTS THE OPERATOR USED IN DOWNHOLE OPERATIONS; AND

(II) PROVIDE A WRITTEN DECLARATION TO THE COMMISSION THAT THE CHEMICAL PRODUCT CONTAINS NO INTENTIONALLY ADDED PFAS CHEMICALS.

(b) (I) (A) FOR A DOWNHOLE OPERATION THAT COMMENCED BEFORE JULY 31, 2023, AND THAT WILL BE ONGOING ON JULY 31, 2023, THE INFORMATION AND DECLARATION REQUIRED TO BE PROVIDED PURSUANT TO SUBSECTION (3)(a) OF THIS SECTION MUST BE PROVIDED TO THE COMMISSION WITHIN ONE HUNDRED TWENTY DAYS AFTER JULY 31, 2023.

(B) THIS SUBSECTION (3)(b)(I) IS REPEALED, EFFECTIVE JULY 1, 2024.

(II) FOR A DOWNHOLE OPERATION THAT COMMENCES ON OR AFTER JULY 31, 2023, THE INFORMATION AND DECLARATION REQUIRED TO BE PROVIDED PURSUANT TO SUBSECTION (3)(a) OF THIS SECTION MUST BE PROVIDED TO THE COMMISSION WITHIN ONE HUNDRED TWENTY DAYS AFTER THE COMMENCEMENT OF THE DOWNHOLE OPERATION.

(c) THE COMMISSION SHALL ENSURE THAT THE INFORMATION AND DECLARATION REQUIRED TO BE PROVIDED UNDER SUBSECTION (3)(a) OF THIS SECTION IS PROVIDED TO THE COMMISSION.

(4) **Change in chemical disclosure information.** IF THERE IS A CHANGE IN THE INFORMATION PROVIDED UNDER SUBSECTION (2)(a)(I) OR (3)(a)(I) OF THIS SECTION, THE DISCLOSER OR OPERATOR, OR IN THE CASE OF DISCLOSURE UNDER SUBSECTION (2)(d) OF THIS SECTION, THE MANUFACTURER, MUST SUBMIT THE CHANGE TO THE COMMISSION WITHIN

THIRTY DAYS AFTER THE DATE THE DISCLOSER, MANUFACTURER, OR OPERATOR FIRST KNEW OF THE CHANGE.

(5) **Chemical disclosure lists.** (a) THE COMMISSION SHALL USE THE CHEMICAL DISCLOSURE INFORMATION TO CREATE A CHEMICAL DISCLOSURE LIST FOR EACH APPLICABLE WELL SITE.

(b) (I) THE COMMISSION SHALL INCLUDE IN THE CHEMICAL DISCLOSURE LIST AN ALPHABETICAL LIST OF THE NAMES AND CHEMICAL ABSTRACTS SERVICE REGISTRY NUMBERS OF EACH CHEMICAL USED IN DOWNHOLE OPERATIONS AT THE WELL SITE.

(II) NOTWITHSTANDING ANY LAW TO THE CONTRARY, THE COMMISSION SHALL INCLUDE THE NAMES AND CHEMICAL ABSTRACTS SERVICE REGISTRY NUMBERS OF ALL CHEMICALS USED IN DOWNHOLE OPERATIONS IN THE CHEMICAL DISCLOSURE LIST AND SHALL NOT PROTECT THE NAMES OR CHEMICAL ABSTRACTS SERVICE REGISTRY NUMBERS OF ANY CHEMICAL AS A TRADE SECRET OR PROPRIETARY INFORMATION. ANY FORMULAS AND PROCESSES CONTINUE TO HAVE TRADE SECRET PROTECTIONS.

(c) THE COMMISSION SHALL NOT INCLUDE IN THE CHEMICAL DISCLOSURE LIST:

(I) THE TRADE NAME OF A CHEMICAL PRODUCT USED IN DOWNHOLE OPERATIONS AT THE WELL SITE; OR

(II) THE TOTAL AMOUNT OF A CHEMICAL IN A CHEMICAL PRODUCT.

(d) NO LATER THAN THIRTY DAYS AFTER AN OPERATOR MAKES THE DISCLOSURES REQUIRED UNDER SUBSECTION (3) OF THIS SECTION, THE COMMISSION SHALL:

(I) POST THE CHEMICAL DISCLOSURE LIST ON THE CHEMICAL DISCLOSURE WEBSITE AND INCLUDE THE DATE OF THE SUBMISSION OF THE CHEMICAL DISCLOSURE LIST TO THE COMMISSION IN THE POST; AND

(II) PROVIDE THE CHEMICAL DISCLOSURE LIST TO THE OPERATOR OF THE APPLICABLE WELL.

(e) THE COMMISSION SHALL:

(I) POST AN UPDATED CHEMICAL DISCLOSURE LIST IF THERE ARE ANY NOTIFICATIONS RECEIVED FROM A DISCLOSER, MANUFACTURER, OR OPERATOR UNDER SUBSECTION (4) OF THIS SECTION AND INCLUDE THE DATE OF THE NOTIFICATION BY THE DISCLOSER, MANUFACTURER, OR OPERATOR IN THE POST; AND

(II) ENSURE THAT:

(A) ALL CHEMICAL DISCLOSURE LISTS AND UPDATED CHEMICAL DISCLOSURE LISTS REMAIN VIEWABLE BY THE PUBLIC;

(B) THE CHEMICAL DISCLOSURE WEBSITE IS SEARCHABLE BY CHEMICAL, DATE OF SUBMISSION OR UPDATE OF A CHEMICAL DISCLOSURE LIST, NAME AND ADDRESS OF THE OPERATOR, AND COUNTY OF THE WELL SITE; AND

(C) THE CHEMICAL DISCLOSURE WEBSITE ALLOWS MEMBERS OF THE PUBLIC TO DOWNLOAD CHEMICAL DISCLOSURE LISTS IN AN ELECTRONIC, DELIMITED FORMAT.

(6) **Community notification.** (a) ON OR BEFORE JULY 31, 2023, AND SUBJECT TO SUBSECTION (6)(b) OF THIS SECTION, AN OPERATOR SHALL PROVIDE THE CHEMICAL DISCLOSURE LIST TO:

(I) ALL OWNERS OF MINERALS THAT ARE BEING DEVELOPED AT THE WELL SITE;

(II) ALL SURFACE OWNERS, BUILDING UNIT OWNERS, AND RESIDENTS, INCLUDING TENANTS OF BOTH RESIDENTIAL AND COMMERCIAL PROPERTIES, THAT ARE WITHIN TWO THOUSAND SIX HUNDRED FORTY FEET OF THE WELL SITE;

(III) THE STATE LAND BOARD IF THE STATE OWNS MINERALS THAT ARE BEING DEVELOPED AT THE WELL SITE;

(IV) THE FEDERAL BUREAU OF LAND MANAGEMENT IF THE UNITED STATES OWNS THE MINERALS THAT ARE BEING DEVELOPED AT THE WELL SITE;

(V) THE SOUTHERN UTE INDIAN TRIBE IF THE MINERALS BEING DEVELOPED AT THE WELL SITE ARE WITHIN THE EXTERIOR BOUNDARY OF THE TRIBE'S RESERVATION AND ARE SUBJECT TO THE JURISDICTION OF THE COMMISSION;

(VI) ALL SCHOOLS, CHILD CARE CENTERS, AND SCHOOL GOVERNING BODIES WITHIN TWO THOUSAND SIX HUNDRED FORTY FEET OF THE WELL SITE;

(VII) POLICE DEPARTMENTS, FIRE DEPARTMENTS, EMERGENCY SERVICE AGENCIES, AND FIRST RESPONDER AGENCIES THAT HAVE A JURISDICTION THAT INCLUDES THE WELL SITE;

(VIII) LOCAL GOVERNMENTS THAT HAVE A JURISDICTION WITHIN TWO THOUSAND SIX HUNDRED FORTY FEET OF THE WELL SITE;

(IX) THE ADMINISTRATOR OF ANY PUBLIC WATER SYSTEM THAT OPERATES:

(A) A SURFACE WATER PUBLIC WATER SYSTEM INTAKE THAT IS LOCATED FIFTEEN STREAM MILES OR LESS DOWNSTREAM FROM THE WELL SITE;

(B) A GROUNDWATER UNDER THE DIRECT INFLUENCE OF A SURFACE WATER PUBLIC WATER SYSTEM SUPPLY WELL WITHIN TWO THOUSAND SIX HUNDRED FORTY FEET OF THE WELL SITE; AND

(C) A PUBLIC WATER SYSTEM SUPPLY WELL COMPLETED IN A TYPE III AQUIFER WITHIN TWO THOUSAND SIX HUNDRED FORTY FEET OF THE WELL SITE; AND

(X) THE DIVISION IF:

(A) THERE IS A HIGH-PRIORITY HABITAT AREA WITHIN ONE MILE OF THE WELL SITE; OR

(B) THERE IS A STATE WILDLIFE AREA, AS DEFINED IN SECTION 33-1-102 (42), OR A STATE PARK OR RECREATION AREA WITHIN TWO THOUSAND SIX HUNDRED FORTY FEET OF THE WELL SITE.

(b) THE CHEMICAL DISCLOSURE LIST MUST BE DISCLOSED IN

ACCORDANCE WITH SUBSECTION (6)(a) OF THIS SECTION WITHIN THIRTY DAYS AFTER THE OPERATOR'S RECEIPT OF THE CHEMICAL DISCLOSURE LIST FROM THE COMMISSION.

(7) **Reporting to the general assembly.** (a) (I) THE COMMISSION SHALL PREPARE AN ANNUAL REPORT THAT INCLUDES A LIST OF THE CHEMICALS USED IN DOWNHOLE OPERATIONS IN THE STATE IN THE PRIOR CALENDAR YEAR.

(II) THE COMMISSION SHALL PRESENT THE ANNUAL REPORT TO THE TRANSPORTATION AND ENERGY COMMITTEE OF THE SENATE AND THE ENERGY AND ENVIRONMENT COMMITTEE OF THE HOUSE OF REPRESENTATIVES, OR THEIR SUCCESSOR COMMITTEES, DURING THE COMMITTEES' HEARINGS HELD PRIOR TO THE 2026 REGULAR SESSION, AND EACH SESSION THEREAFTER, OF THE GENERAL ASSEMBLY UNDER THE "STATE MEASUREMENT FOR ACCOUNTABLE, RESPONSIVE, AND TRANSPARENT (SMART) GOVERNMENT ACT", PART 2 OF ARTICLE 7 OF TITLE 2. THE COMMISSION SHALL ALSO POST THE REPORT ON THE COMMISSION'S WEBSITE.

(b) NOTWITHSTANDING SECTION 24-1-136 (11)(a)(I), THE REQUIREMENT TO REPORT TO THE LEGISLATIVE COMMITTEES CONTINUES INDEFINITELY.

(8) **Rules.** THE COMMISSION MAY PROMULGATE RULES THAT ARE NECESSARY FOR THE IMPLEMENTATION AND ADMINISTRATION OF THIS SECTION.

(9) **Local governments.** NOTHING IN THIS SECTION OR THE RULES PROMULGATED BY THE COMMISSION PURSUANT TO THIS SECTION LIMITS A LOCAL GOVERNMENT FROM ENACTING OR ENFORCING ANY ORDINANCE, REGULATION, OR OTHER LAW RELATED TO THE DISCLOSURE OF ANY CHEMICAL PRODUCT.

(10) **Collection of chemical disclosure information under other provisions of law.** NOTWITHSTANDING ANY LAW TO THE CONTRARY, NOTHING IN THIS SECTION OR THE RULES PROMULGATED BY THE COMMISSION PURSUANT TO THIS SECTION PREVENTS THE COMMISSION, THE STATE, OR A LOCAL GOVERNMENT FROM COLLECTING CHEMICAL DISCLOSURE INFORMATION FROM DISCLOSERS, MANUFACTURERS, OR OPERATORS UNDER ANY OTHER PROVISION OF LAW.

SECTION 3. Appropriation. (1) For the 2022-23 state fiscal year, $61,500 is appropriated to the department of natural resources. This appropriation is from the oil and gas conservation and environmental response fund created in section 34-60-122 (5)(a), C.R.S. To implement this act, the department may use this appropriation for the purchase of information technology services.

(2) For the 2022-23 state fiscal year, $61,500 is appropriated to the office of the governor for use by the office of information technology. This appropriation is from reappropriated funds received from the department of natural resources under subsection (1) of this section. To implement this act, the office may use this appropriation to provide information technology services for the department of natural resources.

SECTION 4. Safety clause. The general assembly hereby finds, determines, and declares that this act is necessary for the immediate preservation of the public peace, health, or safety.

Alec Garnett
SPEAKER OF THE HOUSE
OF REPRESENTATIVES

Steve Fenberg
PRESIDENT OF
THE SENATE

Robin R Jones

Robin Jones
CHIEF CLERK OF THE HOUSE
OF REPRESENTATIVES

Cindi L. Markwell

Cindi L. Markwell
SECRETARY OF
THE SENATE

APPROVED June 8th at 1:33 p.m.
(Date and Time)

Jared S. Polis
GOVERNOR OF THE STATE OF COLORADO

STATE OF NEW MEXICO
DEPARTMENT OF ENERGY, MINERALS AND NATURAL RESOURCES
OIL CONSERVATION COMISSION

IN THE MATTER OF PROPOSED
AMENDMENT TO THE COMMISSION'S
RULES TO ADDRESS CHEMICAL DISCLOSURE
AND THE USE OF PERFLUOROALKYL AND
POLYFLUOROALKYL SUBSTANCES AND
THEIR USE IN OIL AND GAS EXTRACTION,
19.15.2, 19.15.7, 19.15.14, 19.15.16 AND 19.15.25 NMAC **CASE NO. 23580**

SELF-AFFIRMED STATEMENT OF STEPHEN D. RICHARDSON

1. My name is Stephen D. Richardson and I am employed by GSI Environmental Inc. as a Vice President and Principal Engineer. I am familiar with WildEarth Guardians' (WEG) August 23, 2024, Amended Application for Rulemaking (Application), the proposed amendments to the referenced rules as provided in the Exhibit to the Application, and the proposed modifications filed by the New Mexico Oil and Gas Association (NMOGA).

2. I have over 20 years of experience providing academic and consulting expertise in soil and groundwater remediation, environmental site investigation, engineering design, and research and development. I specialize in the application of innovative strategies and technologies to treat conventional and emerging contaminants including per- and polyfluoroalkyl substances (PFAS), chlorinated solvents, 1-4-dioxane, metals, polycyclic aromatic hydrocarbons, and petroleum hydrocarbons in soils and groundwater. I am a licensed Professional Engineer in Louisiana, North Carolina, Texas, and Alberta, Canada. I hold a doctoral degree in Environmental Engineering from the University of North Carolina at Chapel Hill, an M.S. degree in Civil Engineering

NMOGA Exhibit D

(specialization in Environmental Engineering) from Louisiana State University, and a B.A.Sc. degree in Civil (Environmental) Engineering from the University of Waterloo.

3. My educational background and work experience is accurately summarized in **[NMOGA Exhibit D1].** My credentials qualify me to testify as an expert witness in Oil Conservation Commission Case No. 23580. I have been asked by NMOGA to address WEG's amendments to 19.15.2, 19.15.7, 19.15.14, 19.15.16, 19.15.25 NMAC, respectively. As part of my testimony, I will introduce and discuss **NMOGA Exhibits D2 through D14.** These exhibits were either prepared by me or compiled under my direction and supervision.

INTRODUCTION

4. WEG's Application included a (1) written statement outlining WEG's reasoning for requesting the amendments to the above-listed rules; (2) WEG Exhibit 1, which is a copy of existing regulations with WEG's proposed changes in redline; and (3) WEG Exhibit 2, a proposed Public Notice for the rulemaking.

5. PFAS are a diverse class of thousands of fluorinated substances that have been used extensively in industrial, commercial, and consumer applications including aqueous film forming foams (AFFF), electronics, gaskets and seals, friction reducers, outdoor gear and clothing, and non-stick coatings for household products. The term "PFAS" is often applied in reference to a broad group of compounds with a few structural traits in common, such as the presence of fully fluorinated methyl or methylene carbon moieties. This broad grouping combines compounds with distinct properties, including polymerization state (polymers or non-polymers), chemical phase (solid, liquid, or gas), mobility (mobile or immobile), and toxicity (toxic or non-toxic). Further, the molecular

structures often have diverse properties including ionic charge (neutral, zwitterionic, cationic, or anionic) and molecular weight (low or high), that determine a wide range of physicochemical and biological properties such as hydrophobicity, bioaccumulation potential, and water solubility (Korzeniowski et al., 2023), **[NMOGA Exhibit D2]**.

6. FracFocus is a national hydraulic fracturing chemical disclosure registry, where operators report the composition of the hydraulic fracturing fluid used during hydraulic fracturing operations. The trade name, supplier, purpose of the ingredient, maximum concentration in the additive, and maximum concentration in the hydraulic fracturing fluid are disclosed for constituents with Chemical Abstract Service (CAS) numbers. Proprietary or trade secret ingredients are notated in FracFocus but notated in a manner that does not waive recognized proprietary or trade secret protections. While disclosure in FracFocus is voluntary in some states, it is mandatory in New Mexico.

7. Based on the disclosures in FracFocus, two PFAS have been previously reported as ingredients in hydraulic fracturing fluids at select wells in New Mexico. These PFAS, polytetrafluoroethylene (PTFE) and fluoroalkyl alcohol substituted polyethylene glycol (FPEG), are polymeric PFAS that are former components of friction reducers or surfactant additives in hydraulic fracturing fluids. Despite some limited historical use of PFAS in hydraulic fracturing operations, the oil and gas industry has since transitioned away from these compounds in favor of other non-PFAS containing chemistries as evident by the data provided in FracFocus. According to FracFocus, the use of these PFAS in hydraulic fracturing operations in New Mexico is very limited; only 2.2% and 0.38% of the over 9,000 FracFocus records between 2013 and 2023 referenced PTFE or FPEG, respectively. After 2020, PTFE was not listed as an ingredient in hydraulic fracturing

fluids. No records contained reference to FPEG after 2015. From an environmental perspective, these large molecular weight polymeric PFAS are practicably insoluble in water, not bioavailable (i.e., too large to cross the cell membrane) and, as such, are considered "polymers of low concern" (Henry et al., 2018), **[NMOGA Exhibit D3]**.

AMENDED APPLICATION FOR RULEMAKING

8. In the Application, WEG describes PFAS as "an exceptionally toxic group of chemicals that present myriad, long-term, and persistent public health and environmental hazards." (p. 1). This statement is incorrect in a number of ways:

- PFAS are a group of thousands of fluorinated compounds with very different chemical structures and physicochemical properties that ultimately influence the toxicity and fate and transport of these compounds in the environment. For example, heavy molecular weight polymeric PFAS (or fluoropolymers), such as PTFE, are insoluble or poorly soluble in water and, therefore, will not appreciably migrate in a groundwater setting (Henry et al, 2018), **[NMOGA Exhibit D3]**. Non-polymeric PFAS such as PFOA and PFOS behave differently in the environment and exhibit varying toxicities. As a result, these compounds are a focal point for both federal and state regulations in different media.

9. In its Application (pg. 2), WEG cites a 2023 report, *"Fracking with 'Forever Chemicals' in New Mexico: Evidence Shows Oil and Gas Companies Have Used PFAS in New Mexico Wells; Water Risks Especially High for Groundwater-Dependent State"*, authored by Physicians for Social Responsibility ("PSR") ("2023 PSR Report"), **[NMOGA Exhibit D4].** According to WEG, the 2023 PSR Report "confirms that the oil and gas industry is utilizing PFAS in hydraulic fracturing operations in New Mexico".

WEG further states that “[t]he use of PFAS by the oil and gas industry leads to the creation of PFAS contaminated produced water and other nondomestic waste”. These statements are misleading, and the document authored by PSR presents an inaccurate and exaggerated picture of PFAS use in hydraulic fracturing, as described in more detail below.

- The 2023 PSR Report **[NMOGA Exhibit D4]** references information from FracFocus and identified two known PFAS, PTFE (CAS number 9002-84-0) and FPEG (CAS number 65545-80-4), that were disclosed in FracFocus for well activities in New Mexico between 2013 and 2023. No other known PFAS were identified in the PSR document.
    - PTFE, commonly known by its tradename ‘Teflon’, is a fluoropolymer – a large molecule containing a carbon backbone with fluorines attached to each carbon. This structure allows the molecule to be stable (or solid) at high temperatures and water repelling. As a result, PTFE has a multitude of commercial uses including medical devices, cables and wiring, electronics, gaskets and seals, friction reducers, outdoor gear and clothing, and non-stick coatings for household products (ITRC, 2023), **[NMOGA Exhibit D5]**.
    - Like other fluoropolymers, PTFE is not soluble in water. Combined with its high molecular weight and stability, PTFE is not considered bioavailable in the environment (Henry et al, 2018), **[NMOGA Exhibit D3]**.

  - FPEG is a polymeric perfluoropolyether. Falling under the polymer class of PFAS, it has friction reducing properties like PTFE. A former trade name of FPEG is ‘Zonyl’®. which was voluntarily phased out in accordance with the U.S. Environmental Protection Agency’s (USEPA) 2010/2015 PFOA Stewardship Program. (USEPA, 2006), **[NMOGA Exhibit D6]**.
- Based on my review of the FracFocus database, the PSR document correctly listed PTFE and FPEG as listed ingredients in hydraulic fracturing operations in New Mexico. However, the extent of their use in hydraulic fracturing operations and potential risk to the environment was not accurately described in the 2023 PSR report.
  - The use of PTFE and FPEG in hydraulic fracturing fluids is by no means widespread in New Mexico and makes up a very small fraction of the total mass of hydraulic fracturing fluid during each event.
  - Of the 9,169 records between 2013 and 2022, PTFE was reported in 203 records or 2.2%. **PTFE was not a listed ingredient in hydraulic fracturing fluid after 2020.**
  - Between 2013 and 2023 only 34 of the 9,169 records (0.38%) in New Mexico, all from one operator, reported using FPEG. **The use of FPEG in hydraulic fracturing fluid has not been reported since 2015.**
- Excluding PTFE and FPEG, no other known PFAS were listed in the PSR document and, notably, no PFAS that are currently regulated under federal

standards (e.g., drinking water maximum contaminant levels (MCLs)) were listed.

- The 2023 PSR Report also listed ingredients that were described as “nonionic fluorosurfactants” as “potential PFAS” or “likely PFAS”. The assumption that all nonionic fluorosurfactants are “likely PFAS” is speculative, technically inaccurate, and misleading. The USEPA Toxic Substances Control Act (TSCA) (USEPA, 2024a), **[NMOGA Exhibit D7],** defines “PFAS” based on the structure of the compound and the placement of specific moieties within the molecular structure. As a result, not all “nonionic fluorosurfactants” are “PFAS” based on the USEPA’s definition.
- Like PTFE and FPEG, the occurrence of the descriptor “nonionic surfactant” is very limited in the FracFocus database. My review of the FracFocus database identified the descriptor “nonionic fluorosurfactant” in only 24 records of the over 9,000 records (or 0.26%) between 2013 to 2023.
- WEG’s statement that the 2023 PSR report “…confirms that the oil and gas industry is utilizing PFAS in hydraulic fracturing operations in New Mexico” is misleading and implies that PFAS are currently being used in hydraulic fracturing operations in New Mexico, which, according to the FracFocus data itself, is not the case. Although the reference to “PFAS” in the statement, “[t]he use of PFAS by the oil and gas industry leads to the creation of PFAS contaminated produced water and other nondomestic waste” is not technically incorrect, it implies that the class of PFAS (i.e., thousands of compounds) are

present in hydraulic fracturing fluids rather than the limited use of two specific polymeric PFAS *before* 2020.

10. In the Application, WEG also cites the Governor Michelle Lujan Grisham (Governor) and State of New Mexico's petition to the USEPA to list PFAS as hazardous waste under federal law. WEG's statement on page 2 of its Application lacks the context of New Mexico's reasoning for petitioning the USEPA to request listing PFAS as hazardous waste. New Mexico Environment Department (NMED) Secretary James Kenney outlined this reasoning in his 2024 testimony to the United States' Senate Committee on Environment and Public Works hearing, "Examining PFAS as a Hazardous Substance". (Kenney, 2024), **[NMOGA Exhibit D8]**.

11. The basis for the Governor's request to the USEPA stemmed from concerns about elevated concentrations of specific PFAS: releases of AFFF, related to firefighting activities and consumer goods that may enter the environment through domestic wastewater or solid waste facilities that then become sources of contamination. Ultimately, in October 2021, the USEPA determined it would evaluate four (4) individual PFAS to determine whether to regulate them as hazardous waste. These four PFAS are: (1) PFOS, (2) PFOA, (3) PFBS, and (4) GenX. The FracFocus disclosures discussed in the 2023 PSR Report did not include any of the enumerated PFAS (PFOS, PFOA, PFBS, and GenX) that the USEPA agreed to evaluate for listing as hazardous waste. The Governor's request to USEPA mentioned nothing about PFAS from or related to hydraulic fracturing in oil and gas operations, neither did the USEPA's announcement to evaluate the four enumerated PFAS.

12. PFAS in water resources have been the topic of recent studies where groundwater and surface water have been tested. In the limited sampling conducted thus far in New Mexico, detections of PFAS in water resources have been associated with AFFF releases and/or urban areas. (USGS, 2024), **[NMOGA Exhibit D9]**.

19.15.2.7 DEFINITIONS

13. In WEG Exhibit 1, WEG proposes to amend the definitions to the regulations to add eight (8) new defined terms to 19.15.2.7 NMAC. I address certain proposed changes to select definitional terms below.

14. "Chemical" – WEG defines "chemical" as "any element, chemical compound, or mixture of elements or chemical compounds that has a specific name or identity, including a Chemical Abstracts Service number." (p.7). As proposed, this definition is unnecessary and is not useful in the proposed rule. First, the purpose of the proposed rule is to address PFAS in hydraulic fracturing operations, and not every "element, chemical compound, or mixture of elements of chemical compounds", which is unreasonably broad and goes well beyond both the intention of the proposed rule and the public notice provided for in this rulemaking. Second, the proposed definition of "chemical" is not the scientifically accepted version of the term. As defined in the International Union of Pure and Applied Chemistry's Compendium of Chemical Terminology **[NMOGA Exhibit D10]**, "chemical substance" is defined as "matter of constant composition best characterized by the entities (molecules, formula units, atoms) it is composed of". Because the focus of the proposed rule is PFAS, which already has a proposed definition, and the definition that WEG proposes is not scientifically accepted

it stands to reason that this definition of “chemical” be removed from the proposed rule and the OCC should not adopt WEG’s definition of “chemical,” as proposed in 19.15.2.7.

15. “Chemical Disclosure List” – WEG defines “chemical disclosure list” as “a list of all chemicals used in downhole operations at a well site.” (p.7). As it stands, this term and its definition do not provide additional value to the proposed rule and should be removed. The oil and gas industry in New Mexico already discloses the additives in their hydraulic fracturing fluids to FracFocus, a national hydraulic fracturing chemical disclosure registry and, therefore, the addition of a “chemical disclosure list” as defined by WEG would be redundant. As proposed, the definition of “chemical disclosure list” is overly broad, including “all chemicals used in downhole operations at a well site” and goes well beyond the purpose of the proposed rule to address PFAS in hydraulic fracturing operations. As a result, the OCC should not adopt WEG’s definition of “chemical disclosure list” as proposed in 19.15.2.7.

16. “Downhole operations” - WEG provides an overly broad definition of “downhole operations” as follows: “oil and gas production operations that are conducted underground”. (p.8). As proposed, this term and its definition would encompass essentially every activity performed at a well site, extending well beyond the purpose of the proposed revisions to the rule addressing PFAS in hydraulic fracturing operations. For example, as written, WEG’s definition of “downhole operations” would include seismic testing, a process far outside the scope of the present rulemaking. Terminology related to activities specific to hydraulic fracturing (e.g., completion fracturing, treatment), which is already included in the proposed rule, would be more appropriate. As a result, this term and its definition should be removed from the proposed rule and

OCC should not adopt WEG's definition of "downhole operations" as proposed in 19.15.2.7.

17. "PFAS Chemicals" – WEG introduced the term "PFAS chemicals" with a definition as follows: "perfluoroalkyl or polyfluoroalkyl substance with at least one fully fluorinated carbon atom." (p. 9). As proposed, there are several issues with the proposed definition:

- The term "chemicals" is unnecessary and should be removed. The term "PFAS" is an acronym for per- or polyfluoroalkyl substances and, therefore, the use of "chemicals" after "PFAS" in this context is redundant.
- WEG's proposed definition of "PFAS" would include compounds with a single perfluorinated methyl group ($–CF_3$) or a single perfluorinated methylene group ($–CF_2–$). These single $-CF_3$ and $-CF_2-$ moiety compounds are not persistent, degrade in the environment over time, and are utilized in a variety of pharmaceuticals (e.g., Prozac, Lipitor) that are routinely used by the population (Hammel et al., 2022), **[NMOGA Exhibit D11]**. Further, these single $-CF_3$ and $-CF_2-$ compounds are not known to be utilized in hydraulic fracturing operations for oil and gas. Accordingly, using the definition WEG proposes makes no practical or technical sense in the context of this rulemaking.
- WEG's proposed definition is not consistent with the recent definition of PFAS outlined in USEPA's Instructions for Reporting PFAS Under TSCA Section 8(a)(7) (USEPA, 2024a), **[NMOGA Exhibit D7]**, where single $-CF_2-$ and-CF_3 and moiety compounds are excluded from the definition. Other States (e.g., Delaware, Virginia, West Virginia, and Wisconsin) have also recently adopted

or proposed regulations with a definition of PFAS similar to the USEPA's definition, whereby the term "PFAS" are defined as "substances with two or more sequential fully fluorinated carbons."

- For the proposed rule, my recommendation is that the definition of PFAS follow the USEPA's definition where PFAS are defined as substances with two or more sequential fully fluorinated carbons. This proposed definition is consistent with existing regulations and guidance, and appropriately excludes compounds that are not relevant to oil and gas operations (e.g., pharmaceuticals).
- In addition, I recommend that the term "intentionally added PFAS" be included as a definition in the proposed rule to account for the ubiquitous nature of PFAS in the environment and the numerous potential sources of PFAS that are unrelated to oil and gas operations. "Intentionally added PFAS" would be defined as, "PFAS that have been deliberately added to a product to impart a functional or technical effect on the product".
- The OCC should, accordingly, adopt a definition for **PFAS** that is **"substances with two or more sequential fully fluorinated carbons"** and a definition of "**Intentionally added PFAS**" that is **"PFAS that are deliberately added during the manufacture of a chemical product to serve an intended function in the final product"**. The OCC should not adopt WEG's proposed definition of "PFAS Chemicals" in 19.15.2.7 NMAC.

18. "Undisclosed chemicals" – WEG defines "Undisclosed chemicals" as "either chemicals that are listed without a Chemical Abstracts Service number in the

FracFocus database pursuant to 19.15.16.19(B) NMAC, or if a safety data sheet lists ingredients that comprise less than one-hundred percent of the whole chemical product, those chemicals that make up any unlisted portion of a chemical product on a safety data sheet." (p.11). As proposed, this term and its definition would encompass every compound or ingredient in hydraulic fracturing additives regardless of whether the compound is a PFAS and or whether the compound is listed as a trade secret. This definition goes well beyond the intent of the proposed rule to specifically address PFAS in hydraulic fracturing operations. The proposed definition of "undisclosed chemicals" should be removed from the proposed rule and the OCC should not adopt WEG's proposed definition of "Undisclosed chemicals" in 19.15.2.7 NMAC.

19.15.7.16 WELL COMPLETION OR RECOMPLETION REPORT AND LOG

19. In 19.15.7.16(A) WEG inserted new text presenting two additional requirements for the C-105 form. These two requirements mandate (1) that operators include "a chemical disclosure list." (p.12) and (2) "[a] certification that no undisclosed chemicals or PFAS were used in the completion or recompletion of the well . . ." (p.12). The OCC should not adopt WEG's proposed modification to 19.15.7.16(A) as WEG has modified this regulation for the following reasons:

- WEG's proposed addition of "[and the] chemical disclosure list" (p.12) to 19.15.7.16(A) is unnecessary and is already covered under 19.15.16.19(B), Hydraulic Fracturing Disclosure, which requires operators to disclose the ingredients of hydraulic fracturing fluids in the FracFocus chemical registry. Therefore, it would be more appropriate and accurate to replace this term with "Hydraulic fracturing disclosures in FracFocus".

- WEG's proposed text in 19.15.7.16(A) also requires "certification that no undisclosed chemicals or PFAS were used in completion and recompletion of the well . . ." (p.12). The purpose of the proposed revisions to the rule is to specifically address PFAS-containing fluids in hydraulic fracturing operations. The proposed text achieves this by requiring operators to certify that PFAS are not used in the hydraulic fracturing activities. However, the requirement to certify that "no undisclosed chemicals . . . were used in the completion or recompletion of the well" is overly broad and goes beyond the expressed intention of the rule. As a result, the certification requirement for "undisclosed chemicals" should be removed and remain specific to "PFAS". In addition, the term "PFAS" should be amended to include "intentionally added" to acknowledge the ubiquity of PFAS in the environment and the number of unique sources of PFAS that may result in the presence of PFAS in hydraulic fracturing fluids. For example, municipal water, surface water, and private well water are used as the carrier fluid for additives, proppants, etc., during hydraulic fracturing operations. This source water may contain low concentrations of PFAS from other sources unrelated to oil and gas operations or hydraulic fracturing activities and are not the intended focus of this rule. For example, in the case of private water wells, PFAS may be present in groundwater from septic leach fields (Silver et.al., 2023), [**NMOGA Exhibit D11**]. Further, data collected thus far under the fifth Unregulated Contaminant Monitoring Rule (UCMR5) found that greater than 40% of public water systems detected at least one of the 29 PFAS included for analysis. (USEPA, 2024b), **[NMOGA Exhibit D13]**. These results corroborate a 2023 USGS estimate that at least one PFAS would be detected in 45% of drinking water samples (USGS, 2023), **[NMOGA Exhibit D14]**.

20. I recommend that WEG's proposed revisions to the rule be replaced by the following text to provide greater clarity and specificity to 19.15.7.16(A):

> *Within 45 days following the completion or recompletion of a well, the operator shall file form C-105 with the division accompanied by a summary of special tests conducted on the well, including drill stem tests. In addition, the operator shall file a certification that no PFAS were intentionally used in the completion or recompletion of the well, a copy of electrical and radio-activity logs run on the well with form C-105. If the division does not receive form C-105 with attached certification, logs and summaries within the specified 45-day period, the division shall withhold the allowable authorizations for the well or suspend injection authority, as appropriate, until the operator has complied with 19.15.7.16 NMAC.*

19.15.14.9 APPLICATIONS

21. In 19.15.14.9(C), WEG introduces a new proposed certification requirement that states "an applicant for a permit to drill, deepen, or plug back shall certify that they will not introduce any undisclosed chemicals or PFAS in downhole operations of the well" (p.13). As previously stated, the proposed text from WEG is

overly broad, encompassing “any undisclosed chemical” in addition to PFAS, which is the focus of the proposed rule. Further, the reference to “in downhole operations of the well” is equally overly broad and should be replaced with “during hydraulic fracturing of the well” since “hydraulic fracturing” is the impetus for this rule and the term is previously defined. I also recommend that the proposed certification requirement be specific to “intentionally added PFAS” and the reference to the overly broad term “any disclosed chemical” be removed. The OCC should not adopt 19.15.14.9(C) as proposed by WEG but rather replace the proposed text with the following:

> *C. an applicant for a permit to drill, deepen, or plug back shall certify that they will not intentionally introduce PFAS in hydraulic fracturing operations of the well; and . . .*

19.15.16.17 COMPLETION OPERATIONS, SHOOTING AND CHEMICAL TREATMENT OF WELLS

22. In 19.15.16.17(A) WEG inserted proposed language modifying when the New Mexico Oil Conservation Division (OCD) should be notified of a well integrity event, providing: “[If] Completing, [shooting, fracturing or treating a well] has the potential to negatively impact [the producing formation, injection interval,] communicates with other strata…” (p.13). The WEG-proposed terminology “has the potential to negatively impact” is vague, does not lend itself to enforceable actions, and it is unclear what qualitative or quantitative information will be used to determine a “negative impact”. Later in the same sentence for 19.15.16.17(A), the original text of the rule includes the phrase “…create underground waste or contaminate fresh water…,” which provides more specificity than WEG’s proposed terminology and maintains consistency within the rule. I recommend that WEG’s proposed revisions to

19.15.16.17(A) of the rule be replaced by the following text to provide greater clarity and specificity to nature of the event and the conditions for notification to the Division:

> *A. If shooting, fracturing or treating a well injures the producing formation, injection interval, casing or casing seat and may create underground waste or contaminate fresh water, the operator shall within five working days notify in writing the division and proceed with diligence to use the appropriate method and means for rectifying the damage. If shooting, fracturing or chemical treating results in the well's irreparable injury the division may require the operator to properly plug and abandon the well; or*
>
> *B. If a well integrity event occurs from the hydraulic fracturing of a well and causes a loss of containment outside the target strata or damages the well casing or casing seat or may create underground waste or contaminate fresh water, the operator shall within five working days notify in writing the division and proceed with diligence to use the appropriate method and means for rectifying the loss of containment or any damage.*

23. In 19.15.16.17(A)(1), WEG proposes requirements to define the term "diligence" as follows: "diligence shall include but is not limited to verifying casing integrity and isolation of strata. This can include pressure testing in accordance with 19.15.25 NMAC, performing casing integrity logs, cement bond logs and any other means

determined necessary by the operator or required by the division." (p. 14). In the event of a well integrity event, the activities laid out in 19.15.16.17(A)(1) are industry standard operating procedures for verifying casing integrity and isolation of the *target* strata. WEG's proposed text should be modified to reference the "target strata" rather than just "strata" to accurately represent conditions during hydraulic fracturing operations. Therefore, I recommend that the OCC should adopt 19.15.16.17(A)(1) as proposed by WEG, with "strata" replaced with "target strata" as follows:

> *(1) Diligence shall include, but is not limited to, verifying casing integrity and isolation of the target strata. This can include pressure testing in accordance with 19.15.25 NMAC, performing casing integrity logs, cement bond logs, and any other means determined necessary by the operator or required by the division.*

24. In 19.15.16.17(A)(2), WEG proposes "[i]f damage from the shooting, fracturing or treating of a well has the potential to impact surface or groundwater, the operator will test for all chemicals disclosed in previous downhole operations and will use a third party, verified laboratory to conduct any in appropriate [*sic*] testing necessary to verify any potential impact. The testing shall include all chemicals used in the well and may also include but is not limited to PFAS, chemicals listed in 20.6.2. NMAC and chemicals listed in 19.15.29.11(A)(5)(e) NMAC. The division can elect to request more robust sampling than what is proposed by the operator if deemed necessary due to the nature of the potential chemicals." (p. 14) There are several technical issues and inconsistencies with the proposed language, as follows:

- "…potential to impact…" – without a clear definition of "impact", this terminology is ambiguous and open to interpretation. I recommend that the text be modified as follows: ". . . has the *reasonable probability* to *contaminate* surface *water* and groundwater." The term "reasonable probability" is already enacted in the WQCC regulations at 20.6.2.3103 NMAC.
- "The operator will test for all chemicals disclosed in previous downhole operations…" – This statement is vague and overly broad. The term "test" does not specify the media of interest (e.g., groundwater, soil, surface water) and the concept of analyzing for *all* chemicals disclosed in *previous* downhole operations does not make logical sense. If chemicals were used downhole before required disclosures, such as disclosure in FracFocus or elsewhere, it would be difficult, if not, impossible, to disclose *every* chemical *previously* used downhole because there may not necessarily be any record of what was used downhole. Moreover, operator(s) often change over the life of the well. In the event of a well integrity event or spill, the operator would collect samples from groundwater and surface water (if present) and analyze for constituents characteristic of produced water such as chlorides, total petroleum hydrocarbons (TPH), benzene, toluene, ethylbenzene, and xylenes (BTEX), consistent with the constituents listed in Table I of 19.15.29.12 NMAC. Should these indicator parameters be present at concentrations above background levels or relevant state criteria, additional testing might reasonably include disclosed constituents that are *currently* used in hydraulic fracturing operations.

- "…use a third party, verified laboratory…" – the use of certified commercial laboratories is industry standard for analysis of environmental samples. These labs serve as "third party" entities providing unbiased analytical results. The quality of the data will be dictated by the analytical methods (e.g., USEPA Method 1633 Analysis of PFAS in Aqueous, Solid, Biosolids, and Tissue Samples by LC-MS/MS), standard operating procedures of the laboratory, and the analytical capabilities and equipment of the laboratory. The term "verified" is unclear and is not generally accepted language to describe the analytical capabilities and quality control/quality assurance (QA/QC) procedures for a laboratory. Rather, a laboratory is "certified" to perform analysis for specific analytical methods. For example, the USEPA will "certify" a laboratory for analysis of drinking water samples using USEPA-approved analytical methods.
- "The testing shall include all chemicals used in the well and may also include, but is not limited to, PFAS, chemicals listed in 20.6.2. NMAC and chemicals listed in 19.15.29.11(A)(5)(e) NMAC." In the event of a spill or well integrity event, an operator would follow the regulations under 19.15.29.11(A) and analyze, where appropriate, for the constituents listed in 19.15.29.11(A)(5)(e) NMAC. As a result, reference to the Part 29 spills/release rule in New Mexico is unnecessary and redundant. The focus of the proposed rule is PFAS, and, therefore, analysis should be limited to those compounds listed 20.6.2.3103 NMAC, WQCC regulations governing groundwater constituents.
- "…due to the nature of the potential chemicals" – this terminology lacks specificity and does not provide additional value to the statement on the

division's discretion to request a more robust sampling plan. As a result, this terminology should be removed all together.

- For all the reasons outlined above, I recommend that WEG's proposed revisions to the rule be replaced by the following text to provide greater clarity and specificity to 19.15.16.17(A)(2):

> *(2) If a well integrity event of the type enumerated in paragraph B of this section occurs and has a reasonable probability to contaminate surface or groundwater, then:*
>
> > *(b) the division may require the operator to test surface or groundwater within the immediate vicinity of the well integrity event and the division may require the operator to sample for the following contaminants:*
> >
> > > *(i) all contaminants identified on Table I of 19.15.29.12, and as may be amended; and*
> > >
> > > *(ii) all chemicals disclosed in the FracFocus hydraulic fracturing disclosure in accordance with 19.15.16.19(B) NMAC and which are also identified as groundwater contaminants in 20.6.2.3103 NMAC, and as may be amended.*
> >
> > *c) The operator must use an appropriately certified, third-party laboratory to conduct the commensurate sampling and analysis; and will engage with the division to gain*

> *access to valid sampling points within the immediate vicinity of the well integrity event.*

25. In 19.15.16.17(A)(3), WEG proposes, "[i]f it is deemed there is an impact to surface or groundwater the operator shall report the impact as a major release in accordance with 19.15.29 NMAC and respond accordingly" (p. 14). The proposed use of the word "deemed" is incorrect in this instance and should be replaced with more definitive text such as "if analytical sampling and analysis demonstrates . . . ." Further, the term "impact" should be replaced with "if analytical sampling and analysis demonstrates that surface water or groundwater are contaminated as a result of a well integrity event. . . ." Finally, a "major release" as defined in 19.15.29.7(A)(2)(c), (d) is "an unauthorized release of a volume that: (c) may with reasonable probability endanger public health; or (d) substantially damages property or the environment." These conditions also must be met for the operator to report a major release per Part 29 the spill/release rule. I recommend that WEG's proposed revisions to the rule be replaced by the following text to provide greater clarity and specificity to 19.15.16.17(A)(3):

> *C. If the division determines that the well integrity event caused a major release, as defined in 19.15.29 NMAC, then the operator shall report the release in accordance with 19.15.29 NMAC or has polluted, as defined in 19.15.30 NMAC, subsurface water then the operator shall abate the pollution in accordance with 19.15.30 NMAC as applicable.*

CONCLUSION

26. In my opinion, WEG's proposed changes to the rule identified in my testimony are generally too broad and improperly expand beyond the focus of the proposed rule to address PFAS-containing fluids and their use in hydraulic fracturing of oil and gas wells.

27. For the proposed rule, I recommend that the definition of PFAS follow the USEPA's definition where PFAS are defined as substances with two or more sequential fully fluorinated carbons. This proposed definition is consistent with existing regulations and guidance, aligns with scientific publications and articles, and appropriately excludes compounds that are not relevant to oil and gas operations (e.g., pharmaceuticals).

28. In addition, I recommend that the term "intentionally added PFAS" be included in the proposed rule to account for the ubiquitous nature of PFAS in the environment and the numerous potential sources that are unrelated to oil and gas operations. "Intentionally added PFAS" would be defined as "PFAS that have been deliberately added to a product to impart a functional or technical effect on the product".

29. I affirm under penalty of perjury under the laws of the State of New Mexico that the foregoing statements are true and correct. I understand that this self-affirmed statement will be used as written testimony in this case. This statement is made on the date next to my signature below.

_________________________	10/21/2024_
Stephen D. Richardson	Date

EXHIBITS/REFERENCES

Hammel, E., Webster, T. F., Gurney, R., & Heiger-Bernays, W. (2022). Implications of PFAS definitions using fluorinated pharmaceuticals. iScience, 25(4), 104020. https://doi.org/10.1016/j.isci.2022.104020

Henry, B. J., Carlin, J. P., Hammerschmidt, J. A., Buck, R. C., Buxton, L. W., Fiedler, H., Seed, J., & Hernandez, O. (2018). A critical review of the application of polymer of low concern and regulatory criteria to fluoropolymers. Integrated Environmental Assessment and Management, 14(3), 316–334. https://doi.org/10.1002/ieam.4035

ITRC. (2023). PFAS Technical and Regulatory Guidance Document [Factsheet]. Interstate Technology Regulatory Council. https://pfas-1.itrcweb.org/wp-content/uploads/2023/12/Full-PFAS-Guidance-12.11.2023.pdf

Korzeniowski, S. H., Buck, R. C., Newkold, R. M., Kassmi, A. E., Laganis, E., Matsuoka, Y., Dinelli, B., Beauchet, S., Adamsky, F., Weilandt, K., Soni, V. K., Kapoor, D., Gunasekar, P., Malvasi, M., Brinati, G., & Musio, S. (2023). A critical review of the application of polymer of low concern regulatory criteria to fluoropolymers II: Fluoroplastics and fluoroelastomers. Integrated Environmental Assessment and Management, 19(2), 326–354. https://doi.org/10.1002/ieam.4646

Silver, M., Phelps, W., Masarik, K., Burke, K., Zhang, C., Schwartz, A., Wang, M., Nitka, A. L., Schutz, J., Trainor, T., Washington, J. W., & Rheineck, B. D. (2023). Prevalence and Source Tracing of PFAS in Shallow Groundwater Used for Drinking Water in Wisconsin, USA. Environmental Science & Technology, 57(45), 17415–17426. https://doi.org/10.1021/acs.est.3c02826

Testimony of James C. Kenney Cabinet Secretary New Mexico Environment Department To the United States Senate Committee on Environment and Public Works Regarding a hearing on "Examining PFAS as a Hazardous Substance" (2024). https://www.epw.senate.gov/public/_cache/files/f/b/fba4027e-a05a-4334-b446-e187eba8241a/4A3D9461FEFA8DA028DBB0693EE2C60E52FC02166647487DA2F98B5964BBAEAA.03-20-2024-kenney-testimony.pdf

USEPA. (2006). 2010/15 PFOA Stewardship Program Guidance on Reporting Emissions and Product Conten. https://www.epa.gov/sites/default/files/2015-10/documents/pfoaguidance.pdf

USEPA. (2024a). Instructions for Reporting PFAS Under TSCA Section 8(a)(7) (p. 118) [EPA-705-G-2023-3727]. Office of Pollution Prevention and Toxics. https://www.epa.gov/system/files/documents/2024-05/tsca-8a7-reporting-instructions_may2024.pdf

USEPA. (2024b). The Fifth Unregulated Contaminant Monitoring Rule (UCMR 5) Data Summary: July 2024. https://www.epa.gov/system/files/documents/2023-08/ucmr5-data-summary_0.pdf

USGS. (2023). Per- and polyfluoroalkyl substances (PFAS) in United States tapwater: Comparison of underserved private-well and public-supply exposures and associated health implications. Environment International, 178, 108033. https://doi.org/10.1016/j.envint.2023.108033

USGS. (2024). Assessment of per- and polyfluoroalkyl substances in water resources of New Mexico, 2020–21 (Report 2023–5129; Version 1.0: January 2024; Version 1.1: March 2024; Version 1.2: April 2024, Scientific Investigations Report, p. 112). USGS

Publications Warehouse. https://doi.org/10.3133/sir20235129., Gurney, R., & Heiger-Bernays, W. (2022). Implications of PFAS definitions using fluorinated pharmaceuticals. *iScience*, *25*(4), 104020. https://doi.org/10.1016/j.isci.2022.104020

GSI ENVIRONMENTAL

Stephen Richardson, PhD, PE

Vice President/Principal Engineer

Education

Ph.D., Environmental Engineering
University of North Carolina
Chapel Hill, NC, 2010
Dissertation: Effects of In situ Bioremediation Strategies on the Biodegradation and Bioavailability of PAHs in Weathered Manufactured Gas Plant Soil

M.S., Environmental Engineering
Louisiana State University Baton Rouge, LA, 2002
Thesis: Wastewater plume dynamics and bacteria transport within the marshland upwelling system

B.S., Environmental Engineering
University of Waterloo Waterloo, Canada, 2000. *With Honors*

Licenses

Professional Engineer:

- Texas, 116664
- Louisiana, 38348
- North Carolina, 36355
- Alberta, 77284

Affiliations

- Interstate Technology and Regulatory Council
- National Ground Water Association
- Society of American Military Engineers

Contact

E: sdrichardson@gsi-net.com

O: 512.346.4474

C: 919.452.3942

Dr. Richardson is a Vice President and Principal Engineer with GSI Environmental Inc. and has over 20 years of academic and consulting experience in soil and groundwater remediation, environmental site investigation, engineering design, and research and development. Dr. Richardson specializes in the application of innovative strategies and technologies to treat a variety of conventional and emerging contaminants including per- and polyfluoroalkyl substances (PFAS), chlorinated solvents, 1-4-dioxane, metals, polycyclic aromatic hydrocarbons, and petroleum hydrocarbons in soils and groundwater. Dr. Richardson is a Licensed Professional Engineer in Texas, North Carolina, Louisiana, and Alberta, Canada.

His professional experience includes design and implementation of in-situ and ex-situ remedial technologies for PFAS and other contaminants; treatment of non-aqueous phase liquid (NAPL) source zones; litigation support; site investigations of former manufactured gas plants, military bases, Superfund sites, gas stations, and oil and gas refineries; long-term monitoring optimization; stormwater assessments; performance-based remediation; and pre- and post-drill sampling program in areas of oil and gas development. Dr. Richardson has provided expert testimony and consulting support for litigation projects involving various environmental matters, including occurrence of PFAS in drinking water, surface water and groundwater impacts, and cost allocation of environmental liability.

Dr. Richardson is an Adjunct Professor in the Department of Civil, Architectural, and Environmental Engineering at the University of Texas at Austin. He lectures on the fate, transport, risk, assessment, and remediation of conventional and emerging contaminants, including PFAS, in a variety of environmental media (groundwater, surface water, drinking water, soils, sediments, biosolids). Dr. Richardson has authored or co-authored over 20 peer-reviewed journal articles on topics including fate and transport of PFAS, remediation approaches for PFAS and other emerging contaminants, oil and gas development, in situ bioremediation of chlorinated solvents, chemical oxidation, cosolvent flushing and bioavailability of PAHs, and decentralized wastewater treatment.

PROJECT EXPERIENCE

Litigation Expert, Litigation Support, and Consulting Expert

Litigation Expert, Evaluation of PFAS Impacts in Drinking Water, Alabama. Provided technical opinions related drinking water impacts attributed to releases of PFAS to the environment from a landfill. Evaluation of PFAS fate and transport, occurrence data, PFAS treatment technologies, and potential PFAS sources in the watershed. (6039)

NMOGA Exhibit D1

Litigation Support, Evaluation of PFAS Impacts in Drinking Water, New York. Provided technical support to attorneys on drinking water impacts related to potential releases of PFAS to the environment from a former chemical manufacturing plant. Evaluation of fate and transport, occurrence data, and drinking water distribution systems. (5822)

Litigation Support, Lignite Mine and Power Plant Operation, South Texas. Provided litigation support dealing with claims of permit violations, inadequate reclamation, surface and groundwater impacts related to the mine and to power plant wastewater operations. *(5076)*

Arbitration Support, Chemical Manufacturing Plant, South Carolina. Provided technical support in response to a recent arbitration outcome and regulatory compliance and engineering support for the management of several SWMUs on the site.

Composting Facility, British Columbia. Supported the testifying experts in the development of an expert report concerning nuisance impacts associated with a food water composting facility. *(4711)*

Emerging Contaminants & Applied Research

Rapid and Inexpensive Delivery of Particulate Carbon for In Situ PFAS Treatment in Groundwater, Environmental Security Technology Certification Program (ESTCP). Principal Investigator for multi-year DoD-funded project ($1200K) to repurpose a commercially available geotechnical technology for enhanced delivery of granular activated carbon (GAC) or other sorbent material for in situ treatment of PFAS source zones and dilute PFAS plumes in groundwater. *(6471)*

Treatment of Foam Fractionate with Enhanced Contact Plasma, Commercial Client. Technical lead for the bench-scale study aimed at testing the performance of enhanced contact plasma for treatment of a foam fractionate Overall, this study aims to investigate the efficacy of a treatment train approach consisting of foam fractionation for PFAS concentration and electrical discharge plasma for destruction of PFAS. treatment

Impact of Particulate Carbon Amendments on Pollutant Fate in Groundwater, Strategic Environmental Research and Development Program (SERDP). Co-Principal Investigator for a University of Texas led research project on understanding the distribution, capacity, and longevity of particulate carbon amendments in the subsurface. (6182)

Nanofiltration Followed by Electrical Discharge Plasma for Destruction of PFAS and Co-occurring Chemicals in Groundwater: A Treatment Train Approach, Environmental Security Technology Certification Program (ESTCP). Principal Investigator for multi-year DoD-funded project ($1300K) to demonstrate an integrated treatment approach using Nanofiltration to concentrate PFAS and co-contaminant-impacted water and Electrical discharge plasma to treat the concentrate derived from nanofiltration. *(6036)*

An Innovative Plasma Technology for Treatment of AFFF Rinsate from Firefighting Delivery Systems, Environmental Security Technology Certification Program (ESTCP). Co-Principal Investigator for multi-year DoD-funded project ($700K) to demonstrate the operation of a mobile plasma treatment system for the treatment of rinsates from firefighting delivery systems at DoD facilities. *(5565)*

An Innovative Plasma Technology for Treatment of PFAS-Impacted Waters, National Defense Center for Energy & Environment (NDCEE). Co-Principal Investigator for multi-year DoD-funded project ($900K) conduct field demonstrations of a mobile plasma treatment system for the treatment of PFAS-impacted surface water and groundwater at two DoD facilities. *(5555)*

Coupled CO2 flux and radiocarbon technologies: Cross validation and decision support for contamination remediation management. Co-Principal Investigator for a Navy-led project to assess the performance of radiocarbon technologies as a tool for confirming natural attenuation of chlorinated solvents in the subsurface. Responsible for design and execution of the groundwater sampling program and performance modeling. *(5213)*

Pilot Test Performance Monitoring and Optimization Support at a Navy site. Technical lead for a Navy project ($380K) to evaluate the long-term performance of an innovative geotechnical technology for improved delivery of remediation amendments into low permeability zones. The technology generates closely spaced reaction columns within the subsurface to improve diffusion and subsequent treatment of chlorinated solvents entrapped in clays/silts. Responsible for designing and executing a detailed sampling and analysis program to assess key cost and performance metrics for the technology. *(5203)*

Quantification of Methane Emissions from Marginal (Small Producing) Oil and Gas Wells (DOE-NETL DE-FE0031702). Provided technical support for a $1.6 million research project to quantify and characterize emissions from low-producing oil and gas well in multiple U.S. regions. (5140)

PFAS Treatment Using a Mobile Sonolysis Unit, Navy. Co-Principal Investigator for multi-year Navy-funded project ($500K) to demonstrate the operation of a batch sonolysis reactor for treatment of PFAS-impacted groundwater at a Navy base. *(5013)*

Comprehensive Evaluation and Guidance for In Situ Sorption-Degradation Technologies for Sustained Treatment of Chlorinated Solvents in Groundwater, Air Force Civil Engineer Center (AFCEC). Principal Investigator for a multi-year Air Force-funded project ($960K) to assess the performance of particulate carbon amendments for the treatment of chlorinated solvents in complex media. *(4967)*

An Enhanced Contact Electrical Discharge Plasma Reactor: An Effective Technology to Degrade Per- and Poly-Fluoroalkyl Substances (PFAS), Air Force Civil Engineer Center (AFCEC). Co-Principal Investigator for multi-year Air Force-funded project ($990K) to demonstrate the operation of an enhanced contact electrical discharge plasma reactor for treatment of extracted poly- and perfluoroalkyl substances (PFAS) contaminated groundwater (e.g., investigation derived waste [IDW] purge water or other sources) at Air Force bases and facilities. *(4710)*

Performance Groundwater Monitoring for Innovative Technology for Remediation of Low-Permeability Media. Technical lead for performance monitoring program ($55K) to assess the initial performance of a recently implemented biotic/abiotic pilot-scale remedy at a Navy site.

Methane Emissions Detection and Quantification, U.S. Department of Energy–National Energy Technology Laboratory (DOE-NETL). Provided technical support for two research projects ($2M) to measure and quantify component-specific methane emissions from underground natural gas storage wells and surface infrastructure and reduce uncertainty in the U.E. EPA's national greenhouse gas inventory. (4502)

New Application of a Geotechnical Technology to Remediate Low-Permeability Media Research Project, Environmental Security Technology Certification Program (ESTCP). Principal investigator (PI) for a multi-year DoD-funded research project ($1020K) to demonstrate an innovative technology for improved delivery of remediation amendments into low permeability zones at contaminated sites. *(4460)*

Anaerobic Bioremediation of Chlorinated Solvent DNAPL Research Project, Air Force Civil Engineer Center (AFCEC). PI for a multi-year Air Force-funded research project ($495K) to demonstrate enhanced dissolution and biodegradation of a chlorinated solvent DNAPL using an emulsified oil technology formulated with a slow-release pH buffer and a bioaugmentation culture. *(3945)*

1,4-Dioxane *In situ* Treatment Research Project, Air Force Civil Engineer Center (AFCEC). Principal investigator (PI) and project manager for a multi-year Air Force-funded research project ($698K) to demonstrate a simple, low-cost approach for enhancing in situ cometabolic biodegradation of 1,4-dioxane and TCE by creating distinct geochemical zones within a comingled plume. *(3939)*

Environmental Impact of Gas Shale Development Research Project, Research Partnership to Secure Energy for America (RPSEA) program. Technical lead for a multi-year Department of Energy-funded research project ($4.4 M) to provide scientific support and guidance on best management practices to characterize air emissions from fracturing fluid ponds, baseline water quality (e.g., dissolved gases) in residential water wells; and produced/flowback water. *(3875)*

Site Investigation & Remediation

Engineering Support, Navy Base, Hawaii. Led the GSI team supporting the U.S. Navy's prime contractor in the evaluation of potential water supply impacts at the facility. This multifaceted approach included multi-level site investigations, geochemical assessments, hydraulic evaluations, vadose zone and groundwater modeling, geophysics, natural attenuation evaluation, environmental forensics, data visualization, risk assessment, and remedial alternatives evaluation. *(4902)*

Assessment of Methane Distribution in Subsurface, Property Development, Houston, Texas. Provided technical support to a developer regarding the presence of elevated methane in the surface from previously buried construction and vegetative debris. Responsible for assessing the source of methane, occurrence and extent of methane, and estimated volumes of organic material in the subsurface. In addition, site management options were presented along with estimated costs. (6559)

Site Assessment and Remediation, Crude Oil Pipeline Release, Crockett County, Texas. Project lead for the assessment and remediation of a large crude oil pipeline release to a deep, fractured karst aquifer. Supported the development of a delineation field program and design of a product recovery system. *(5988)*

Site Assessment and Technical Support, Natural Gas Pipeline Replacement, North Texas. Provided technical support to a natural gas supplier for replacement of a natural gas supply line through an unpermitted municipal solid waste landfill containing VOCs and methane in soil and groundwater. (5566)

Third-party Technical Support, Coal-Fired Power Plant, Texas. Provided a third-party review to ensure groundwater assessment activities under the monitoring program complied with Federal CCR rules. Presented findings and recommendations to the client. *(5395)*

Site Assessment & Remediation, Truck Stop, Fabens, Texas. Project manager for the assessment of a legacy LPST case at an active truck stop with an LNAPL and dissolved phase groundwater plume from an on-site fuel release. Responsible for development of the assessment and monitoring strategy for groundwater impacts at the site. Negotiated with the TCEQ and prepared a successful technical case for regulatory closure. (5239)

Site Remediation and Regulatory Compliance for a Coal Fired Power Plant, South Texas. Lead engineer for the design and implementation of a i) groundwater extraction system for recovery of metals-impacted groundwater and ii) an interceptor trench to collect surficial seepage from a closed pond. Responsible for maintaining regulatory compliance under both federal (CCR Rules) and state programs and conducting soil and groundwater investigations at the Plant according to the requirements of these programs. Additional tasks include evaluation of detection and assessment monitoring results, identification of statistically significant increases (SSIs) above respective groundwater protection standards, and assessment of corrective measures options. *(5076)*

Performance-Based Remediation Project, Air Force Base, Kansas. Project manager for an Air Force Performance-Based Remediation project to address chlorinated solvent-contaminated groundwater. Responsible for selection, design, and performance of the remedial approach, design of the site assessment program (e.g., installation and sampling of groundwater monitoring well networks), development of corrective measures study reports, remedial investigation/feasibility reports, engineering evaluation/cost analysis reports, analysis of performance data to support remedial decision making, and project schedules. *(3969)*

In situ Bioremediation, Industrial Site, Indiana. Assisted in the development of conceptual designs, treatability studies, and final selection, design, and implementation of in-situ reactive soil mixing using zero-valent iron for treatment of chlorinated solvents in groundwater. *(3895)*

Iron Mediated Bioremediation, Naval Base, Florida. Technical lead for a pilot test program to evaluate an iron-mediated method to reduce sulfide toxicity and maintain optimal pH for reestablishment of TCE dehalorespiration. Designed the pilot demonstration, supervised laboratory batch experiments, reviewed analytical data, developed work plan, and provided PM technical support.

Commercialization of Bioremediation Product (Vadose Oil Substrate; VOS™). Co-developed and commercialized a new bioremediation product with researchers at Savannah River National Laboratory that promotes anaerobic biodegradation of residual chlorinated solvents in the vadose zone.

Site Assessment and Remedial Activities, Former Gas Station, Athabasca, Canada. Project manager responsible for coordinating and executing all tasks involved in the excavation and landfarming of petroleum hydrocarbon-contaminated soil from a former gas station. Responsibilities included site assessment, UST removal, remedial design, oversight of construction equipment and excavation activities, coordination of subcontractors, landfarm site selection and preparation, sample collection, regulatory and client interaction, and reporting.

Site Assessment and Remedial Activities, Former Gas Station, Edmonton, Canada. Project manager responsible for all field activities involved with the excavation of petroleum hydrocarbon-contaminated soil from a former gas station. Responsibilities included site assessment, oversight of construction equipment and excavation activities, coordination of subcontractors, sample collection, regulatory and client interaction, and reporting.

Stormwater Impact Assessment at a Metals Galvanizing Plant, Edmonton, Canada. Project manager for a stormwater impact assessment for a metals galvanizing plant in response to high levels of zinc in a nearby catch basin. Responsible for client correspondence and reporting, field program design, work plan and technical report development, data analysis, and project scheduling and budget.

Operation and Maintenance of a Constructed Wetland Project at an Active Oil and Gas Refinery, Red Deer, Canada. Project manager for the operation, maintenance, and routine sampling of a surface-flow constructed wetland to treat nutrient- and metals-contaminated groundwater at an active oil and gas refinery.

Soil Excavation Project at a Former Oil and Gas site, Devon, Canada. Supervised the excavation of petroleum-contaminated soils from a former oil and gas facility location. Directed field activities as site engineer to achieve compliance with soil quality benchmarks for land redevelopment.

Soil Excavation Project at a Former Gas Station site, Edmonton, Canada. Supervised the excavation of petroleum-contaminated soils from a former gas station. Directed field activities and collected soil samples to determine the extents of the excavation.

Groundwater Recovery System at an Active Oil and Gas Production Facility. Coordinated the installation of a groundwater recovery system to collect petroleum- and salt-contaminated groundwater at an oil and gas production facility.

Soil Vapor Extraction Projects at Several Operating Gas Stations. Monitored and evaluated the performance of several pilot-scale soil vapor extraction systems at operating gas stations. Responsible for routine maintenance and gas sample collection.

Phase II Environmental Site Assessments at Gas Production Facilities and Active Gas Stations. Responsible for site delineation, remedial proposal development, and correspondence with client and government agencies as part of pre-remedial activities

Remedy Optimization

Remedy Optimization at Complex Navy Bioremediation Sites, Naval Facilities Engineering Command (NAVFAC). Technical lead for a Navy-funded project ($440K) to: i) develop guidance to Navy RPMs at bioremediation-treated sites that have experienced sub-optimal performance with an optimum path forward and ii) provide guidance on the viability of bioremediation to Navy RPMs at sites contemplating treatment. Responsible for designing and executing a detailed sampling and analysis program at bioremediation sites to determine the role of relatively less-studied factors potentially governing biological treatment success. *(5010)*

Optimization Review, Garland Creosoting Superfund Site, Longview, Gregg County, Texas, EPA Region 6. Technical lead for an optimization review that evaluated the site's current conceptual site model, the current monitoring network and sampling program, progress towards remedial action objectives, remedy performance, and data management and analysis. *(3948)*

Optimization Review, Bunker Hill Mining and Metallurgical Site, Coeur d'Alene Basin, Shoshone County, Idaho, EPA Region 10. Managed an optimization study to develop a framework for short-term and long-term data collection, management, and interpretation for various remedial actions across the basin. Support for the remedial action effectiveness plan included review of performance objectives for the proposed remedy and development of a template for assessing remedial effectiveness and short-term and long-term monitoring at the site. *(3948)*

Groundwater Monitoring Network Optimization, Newmark Superfund Site, San Bernardino, California, EPA Region 9. Technical lead for an optimization review to improve the efficiency of the current monitoring strategy by evaluating stability of the groundwater plume, sufficiency and redundancy of monitoring locations and the appropriate frequency of network sampling. *(3948)*

Technology Transfer & Training

Trainer, Navy Remediation Innovative Technology (RITS) Seminars. Developed and presented training material on in situ application of particulate carbon amendments for groundwater remediation. Audience was Navy personnel and contractors, and 2.5-hour training module was presented at five different locations (Jacksonville, Norfolk, Washington, Silverdale, and Honolulu). (6135).

Content Development and Technical Review of CLU-In Focus Areas (1,4-Dioxane, Fractured Rock, Horizontal Wells. Provided technical review content for the Clu-In website related to installation, operation, and applications of horizontal wells in environmental remediation.

Technical Review of CLU-In Focus Area on 1,4-Dioxane. Provided technical review of 1,4-Dioxane content for the Clu-In website, including: Policy and Guidance, Chemistry and Behavior, Occurrence, Toxicology, Detection and Site Characterization, and Treatment Technologies. Recommendations for additional resources (e.g., publications, journal articles, reports) were provided.

Produced Water Fact Sheet, International Petroleum Industry Environmental Conservation Association. Developed a 4-page fact sheet summarizing the current state of literature on the composition, characterization, generation and reuse, and treatment costs for produced water generated in the U.S. and internationally. *(5101)*

PUBLICATIONS

Freedman, M., Mumford, K.G., Danko, A., Hart, D.M., **Richardson, S.D.** (2023). Development and application of a principal component analysis trajectory method to assess bioremediation progress at two TCE-impacted sites. Groundwater Monitoring & Remediation. 43 (2): 90-97.

Richardson, S. D., Kolz, J., Hart, D. M., Long, J. A., Johnson, N. W., Denn, A. R., & Newell, C. J. (2022). A novel application of a geotechnical soil stabilization technology for improved delivery of remedial amendments. Remediation, 1– 14. https://doi.org/10.1002/rem.21740

Newell, C. J., Javed, H., Li, Y., Johnson, N. W., **Richardson, S. D.**, Connor, J. A., & Adamson, D. T. (2022). Enhanced attenuation (EA) to manage PFAS plumes in groundwater. Remediation, 32, 239– 257. https://doi.org/10.1002/rem.21731

Kulkarni, P. R., Aranzales, D., Javed, H., Holsen, T., Johnson, N. W., **Richardson, S. D.**, Thagard, S. M., & Newell, C. J. (2022). Process to separate per- and polyfluoroalkyl substances from water using colloidal gas aphrons. Remediation, 32, 167– 176. https://doi.org/10.1002/rem.21716

Kulkarni, P.R., **Richardson, S.D.**, Nzeribe, B.N., Adamson, D.T., Kalra, S.S., Mahendra, S., Blotevogel, J., Hanson, A., Dooley, G., Maraviov, S., & Popovic, J. (2022). Field Demonstration of a Sonolysis Reactor for Treatment of PFAS-Contaminated Groundwater. Journal of Environmental Engineering, 148(11), November 2022.

Molofsky, L.J., J.A. Connor, C. Van De Ven, M.P. Hemingway, **S.D. Richardson**, B. A. Strasert, S.M. Paquette, T.M. McGuire (2021). A Review of Physical, Chemical, and Hydrogeologic Characteristics of Stray Gas Migration: Implications for Investigation and Remediation, Science of the Total Environment.

Singh, R. K., Multari, N., Nau-Hix, C., Anderson, R.H., **Richardson, S.D.,** Holsen, T.M., and Mededovic Thagard, S., (2019). "Rapid Removal of Poly- and Perfluorinated Compounds from Investigation-Derived Waste (IDW) in a Pilot-Scale Plasma Reactor." Environmental Science & Technology, in press.

Borden, R.C., **Richardson, S.D.,** and Bodour A.A. (2019). Enhanced Reductive Dechlorination of TCE in an Acidic DNAPL Impacted Aquifer, Journal of Environmental Management, 237:617-628.

Smith, A.P., Van De Ven, C.J.C, and **Richardson, S.D.,** (2018). Current Water Management Practices, Challenges, and Innovations for US Unconventional Oil and Gas Development, Current Sustainable Renewable Energy Reports.

Molofsky, L.J., **Richardson, S.D.,** Gorody, A.W., Baldassare, F., Connor, J.A., McHugh, T.E., Smith, A.P., Wylie, A.S., and Wagner, T., (2017). Purging and other sampling variables affecting dissolved methane concentration in water supply wells, Science of the Total Environment, 618, 998-1007.

Zhu, J., Parris, T.M., Taylor, C.J., Webb, S.E., Davidson, B., Smath, R., **Richardson, S.D.,** Molofsky, L.J., Kromann, J.S., and Smith, A.P. (2017). Assessing Methane in Shallow Groundwater in Unconventional Oil and Gas Play Areas, Eastern Kentucky, Groundwater.

Molofsky, L.J., **Richardson, S.D.,** Gorody, A.W., Baldassare, F.; McHugh, T.E.; and Connor, J.A. (2016). Effect of Different Sampling Methodologies on Measured Methane Concentrations in Groundwater Samples, Groundwater, 54: 669–680.

Molofsky, L.J., Connor, J.A., McHugh, T.E., **Richardson, S.D.,** Woroszlyo, C., and Alavarez, P.A. (2016). Environmental Factors Associated with Natural Methane Occurrence in the Appalachian Basin, Groundwater, 54:656-668.

Connor, J.A., Molofsky, L.J., **Richardson, S.D.,** and Bianchi-Mosquera, G.C. (2015). Environmental Issues and Answers Related to Shale Gas Development. In Proceedings of the 2015 SPE Latin American and Caribbean Health, Safety, Environment and Sustainability Conference, Bogotá, Colombia, July 7-8, 2015.

Connor, J.A., Molofsky, L.J., **Richardson, S.D.,** and Bianchi-Mosquera, G.C. (2015). Distinguishing Natural vs. Anthropogenic Methane in Groundwater in a Shale Gas Basin. In Proceedings of the 2015 SPE Latin American and Caribbean Health, Safety, Environment and Sustainability Conference, Bogotá, Colombia, July 7-8, 2015.

Singleton, D.R., Jones, M.D., **Richardson, S.D.,** and Aitken, M.D. (2012). Pyrosequence analyses of bacterial communities during simulated in situ bioremediation of polycyclic aromatic hydrocarbon-contaminated soil, Applied Microbiology and Biotechnology, November 2012.

Richardson, S.D., Jones, M.D., Singleton, D.R., and Aitken, M.D. (2012). Long-term simulation of in situ biostimulation of polycyclic aromatic hydrocarbon-contaminated soil, Biodegradation, 23(4):621-633.

Richardson, S.D., Elkins, J.B., Rogers, T., Beckwith, W., Riha, B.D., Noonkester, J.V., Looney, B.B., Hyde, W. K., Walker, R.W. (2012). Application of Biodegradable Oils (VOS™) for Treatment of Chlorinated Ethenes in the Vadose Zone. In Proceedings of the 2012 Waste Management Symposia, Phoenix, USA, February 27-March 2, 2012.

Hu, J., Nakamura, J., **Richardson, S.D.,** and Aitken, M.D. (2012). Evaluating the effects of bioremediation on genotoxicity of polycyclic aromatic hydrocarbon-contaminated soil using genetically engineered, higher eukaryotic cell lines, Environmental Science and Technology, 46(8):4607-4613.

Richardson, S.D., and Aitken, M.D. (2011). Desorption and bioavailability of polycyclic aromatic hydrocarbons in contaminated soil subjected to long-term in situ biostimulation, Environmental Toxicology and Chemistry, 30(12):2674-2681.

Schultz Birak, P., Newman, A.P., **Richardson, S.D.,** Hauswirth, S.C., Pedit, J.A., Aitken, M.D., and Miller, C.T. (2011). Cosolvent flushing for the remediation of PAHs from former manufactured gas plants, Journal of Contaminant Hydrology, 126:72-84.

Singleton, D.R., **Richardson, S.D.,** and Aitken, M.D. (2011). Pyrosequence analysis of bacterial communities in aerobic bioreactors treating polycyclic aromatic hydrocarbon-contaminated soil, Biodegradation, 22:1061-1073.

Richardson, S.D., Lebron, B.L., Miller, C.T., and Aitken, M.D. (2011). Recovery of phenanthrene-degrading bacteria after simulated in situ persulfate oxidation in contaminated soil, Environmental Science and Technology, 45(2):719-725.

Park, D.R., Ball, L.M., **Richardson, S.D.,** Zhu, H.-B., and Aitken, M.D. (2008). Oxidative mutagenicity of polar fractions from polycyclic aromatic hydrocarbon-contaminated soils, Environmental Toxicology and Chemistry, 27(11):2207-2215.

Singleton, D.R., **Richardson, S.D.,** and Aitken, M.D. (2008). Effects of enrichment with phthalate on polycyclic aromatic hydrocarbon biodegradation in contaminated soil, Biodegradation, 19(4):577-587.

Richardson, S.D. and Rusch, K.A. (2005). Fecal coliform removal within a Marshland Upwelling System consisting of Scatlake soils, Journal of Environmental Engineering, 131(1):60-70.

Richardson, S.D., Willson, C.S., and Rusch, K.A. (2004). Use of Rhodamine Water Tracer in the Marshland Upwelling System, Ground Water, 42(5):678-688.

Integrated Environmental Assessment and Management — Volume 19, Number 2—pp. 326–354

Received: 9 March 2022 | Revised: 7 June 2022 | Accepted: 7 June 2022

Critical Review

A critical review of the application of polymer of low concern regulatory criteria to fluoropolymers II: Fluoroplastics and fluoroelastomers

Stephen H. Korzeniowski,[1] Robert C. Buck,[2] Robin M. Newkold,[2] Ahmed El kassmi,[3] Evan Laganis,[3] Yasuhiko Matsuoka,[4] Bertrand Dinelli,[5] Severine Beauchet,[5] Frank Adamsky,[6] Karl Weilandt,[7] Vijay Kumar Soni,[8] Deepak Kapoor,[9] Priyanga Gunasekar,[9] Marco Malvasi,[10] Giulio Brinati,[10] and Stefana Musio[10]

[1]BeachEdge Consulting LLC, Media, Pennsylvania, USA
[2]The Chemours Company, Wilmington, Delaware, USA
[3]AGC Chemicals Americas, Exton, Pennsylvania, USA
[4]AGC Performance Chemicals General Division, Tokyo, Japan
[5]Arkema, Colombes, France
[6]Daikin America Inc., Decatur, Alabama, USA
[7]Advanced Materials Division, 3M Center, 3M Company, St. Paul, Minnesota, USA
[8]Gujarat Fluorochemicals Limited, Noida, Uttar Pradesh, India
[9]Gujarat Fluorochemicals GmbH, Regus Centre Watermark, Hamburg, Germany
[10]Solvay Specialty Polymers, V.le Lombardia, Bollate, (MI), Italy

Abstract

Fluoropolymers are a distinct class of per- and polyfluoroalkyl substances (PFAS), high molecular weight (MW) polymers with fluorine attached to their carbon-only backbone. Fluoropolymers possess a unique combination of properties and unmatched functional performance critical to the products and manufacturing processes they enable and are irreplaceable in many uses. Fluoropolymers have documented safety profiles; are thermally, biologically, and chemically stable, negligibly soluble in water, nonmobile, nonbioavailable, nonbioaccumulative, and nontoxic. Although fluoropolymers fit the PFAS structural definition, they have very different physical, chemical, environmental, and toxicological properties when compared with other PFAS. This study describes the composition, uses, performance properties, and functionalities of 14 fluoropolymers, including fluoroplastics and fluoroelastomers, and presents data to demonstrate that they satisfy the widely accepted polymer hazard assessment criteria to be considered polymers of low concern (PLC). The PLC criteria include physicochemical properties, such as molecular weight, which determine bioavailability and warn of potential hazard. Fluoropolymers are insoluble (e.g., water, octanol) solids too large to migrate into the cell membrane making them nonbioavailable, and therefore, of low concern from a human and environmental health standpoint. Further, the study results demonstrate that fluoropolymers are a distinct and different group of PFAS and should not be grouped with other PFAS for hazard assessment or regulatory purposes. When combined with an earlier publication by Henry et al., this study demonstrates that commercial fluoropolymers are available from the seven participating companies that meet the criteria to be considered PLC, which represent approximately 96% of the global commercial fluoropolymer market. *Integr Environ Assess Manag* 2023;19:326–354. © 2022 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Applications, Fluoropolymers, Low concern, PFAS, Property Combinations

INTRODUCTION

“Fluoropolymers are high MW polymers with fluorine atoms directly attached to their carbon-only backbone” (Ebnesajjad, 2017). The carbon–fluorine (C–F) bond is the strongest bond between carbon and another atom and imparts unique, outstanding, and beneficial properties and extraordinary functional performance to fluoropolymers (Ameduri, 2020; Ameduri & Sawada, 2017a, 2017b; Banks et al., 1994; Fluoropolymer Products Group of Plastics Europe [FPG], 2021a; Scheirs, 2007). These properties

This article contains online-only Supporting Information.

Correspondence Stephen H. Korzeniowski, BeachEdge Consulting LLC, Media, PA, USA.
Email: shkorzo@gmail.com

DOI: 10.1002/ieam.4646

NMOGA Exhibit D2

include chemical, biological, and thermal stability, heat and chemical resistance, unique dielectric properties, and durability. Additional fluoropolymer properties include fire resistance, weather resistance, nonwetting, and nonstick. Fluoropolymers are regarded as irreplaceable in many applications because their unique combination of specific properties, which are critical to ensure optimal performance in many applications, cannot be achieved or guaranteed by alternative materials (FPG, 2021a, 2017; Henry et al., 2018; Performance Fluoropolymer Partnership of the American Chemistry Council [PFP], 2020).

Per- and polyfluoroalkyl substances (PFAS), a universe of substances with widely diverse properties that have been used in industrial and consumer applications since the 1950s, include fluoropolymers as a distinct class (Buck et al., 2011; Henry et al., 2018). A single, globally harmonized definition for PFAS has not yet been agreed upon. PFAS have been defined differently based on their structure and atomic composition (Buck et al., 2021; Wallington et al., 2021). For example, the USEPA's working PFAS structure definition is “a structure that contains the unit R-CF_2-CF(R′)(R″), where R, R′, and R″ do not equal “H” and the carbon–carbon bond is saturated (note: branching, heteroatoms, and cyclic structures are included” (USEPA, 2021a). The European Chemicals Agency (ECHA) employed a much broader PFAS structural definition (ECHA, 2020). A recent Organisation for Economic Cooperation and Development (OECD) report, which defined PFAS as fluorinated substances that contain in their structure at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), that is, with a few noted exceptions, any chemical with at least a perfluorinated methyl group ($–CF_3$) or a perfluorinated methylene group ($–CF_2–$; OECD, 2021). This report acknowledges that the term “PFAS” is broad, general, and nonspecific, which does not inform whether a compound presents risk or not, but only communicates that the compounds under this term share the same structural trait of having a fully fluorinated methyl or methylene carbon moiety. Further, the report highlights that, among the substances defined as PFAS, there are distinct substances with very different properties: polymers and nonpolymers; solids, liquids and gases; persistent and nonpersistent substances; highly reactive and inert substances; mobile and insoluble (immobile) substances; and (eco) toxic and nontoxic chemicals. In addition, the report recognizes that PFAS have diverse molecular structures (e.g., neutral, anionic, cationic, or zwitterionic; with or without aromatic rings; nonpolymers or polymers; low or high molecular weight (MW), and thus diverse physical, chemical, and biological properties (e.g., involatile or volatile; water soluble or water insoluble; reactive vs. inert; bioaccumulative or nonbioaccumulative) and as such highly recommends that such diversity be properly recognized and communicated in a clear, specific, and descriptive manner when communicating about PFAS.

There is considerable media and public confusion and misunderstanding regarding PFAS, as the many different chemicals and groups are often not clearly differentiated under the broad term PFAS. Per- and polyfluoroalkyl substances, a large, diverse group of substances with vastly different properties, is too broad to allow effective, science-based assessment and regulation of chemical compounds as an entire group. This point has been raised in recent publications that suggest approaches to effectively group PFAS for regulatory assessment (American Chamber of Commerce in Europe [Amcham], 2020a; Buck et al., 2021; Bundesverband der Deutschen Industrie e.V. [BDI], 2021; Fiedler et al., 2020; Miller et al., 2020; Orgalim, 2021; Royal Society of Chemistry [RSC], 2021; Sha et al., 2019; Wallington et al., 2021). A clear understanding of the origin of PFAS found in the environment, the PFAS that are commercially relevant (Buck et al., 2021), and assessment of their properties are needed to be able to determine which classes of PFAS require management action. PFAS must be assessed based on their chemical, physical, thermal, and biological property differences and uses (Amcham, 2020a; BDI, 2021; Buck et al., 2021; RSC, 2021; Wallington et al., 2021). As regulatory frameworks, such as the EU REACH regulation, continue to evolve, more work is needed to distinguish clearly among PFAS based on their properties to assure that regulations are appropriate in scope, proportionate, and are science-based.

Per- and polyfluoroalkyl substances are divided into two primary categories: nonpolymers and polymers (Buck et al., 2011). Polymeric PFAS, generally known as “fluorinated polymers,” include fluoropolymers (discussed here), perfluoropolyethers (PFPE), and side-chain fluorinated polymers (SCFP; Buck et al., 2011; Henry et al., 2018 and Supporting Information: Figure 6.1). This article deals strictly with fluoropolymers. Neither PFPE nor SCFP are discussed here.

The nonpolymer category includes perfluoroalkyl substances and polyfluoroalkyl substances. Certain nonpolymer PFAS substances, for example, short- and long-chain per- and polyfluoroalkyl carboxylic acids and sulfonic acids, received regulatory scrutiny recently due to their toxicity, as well as their persistence, potential to bioaccumulate, and/or mobility in the environment. Regulatory processes have been launched worldwide to address these concerns related to specific nonpolymer PFAS. These targeted regulatory measures have evolved increasingly into restrictions on the entire family of PFAS. For example, five Member States of the European Economic Area have initiated a procedure to prepare a joint restriction proposal under the EU REACH Regulation to limit the risks to human health and the environment from the manufacture and use of all substances in the PFAS family based on structure alone (ECHA, 2020). Although fluoropolymers fit the PFAS structural definition, they have vastly different physicochemical, environmental, and toxicological properties than other PFAS in addition to substantial societal benefits and importance (Fluoropolymer Products Group of Plastics Europe [FPG], 2017, 2021a). For these reasons, fluoropolymers should be considered separately and not aggregated with all other PFAS for regulatory action. Concurrently, the USEPA prepared a PFAS Strategic Roadmap laying out how it plans to evaluate and potentially regulate PFAS (USEPA, 2021a). Recognizing that there are many PFAS very diverse in their physical form, chemical structure and composition, functional characteristics, and toxicity profiles, USEPA "is conducting new research to better understand the similar and different characteristics of specific PFAS and whether and how to address groups and categories of PFAS."

Fluoropolymers have documented safety profiles, are thermally, biologically, and chemically stable, negligibly soluble in water, nonmobile, nonbioavailable, nonbioaccumulative, and nontoxic (Henry et al., 2018). Some fluoropolymers have been demonstrated to meet the "polymers of low concern" (PLC) criteria, and as such do not present notable concern for human health or the environment (Henry et al., 2018). PLC criteria were developed over time within regulatory frameworks around the world as an outcome of chemical hazard assessment processes, which identified physical–chemical properties of polymers that determine polymer bioavailability and thereby report a polymer's potential hazard. For example, many of the physicochemical properties, such as MW, limit the ability of a polymer to cross the cell membrane and therefore limit its bioavailability (Kostal, 2016; Lipinski et al., 2001; USEPA, 2012). The USEPA built on this knowledge to adopt a polymer exemption rule to exempt low-hazard polymers from certain regulatory notification requirements under the Toxic Substances Control Act's (TSCA) new chemicals program (United States Federal Register [USFR], 1984). An OECD expert group on polymers reached consensus on these criteria and their respective metrics, documenting the data required for a polymer to qualify as a PLC to human health and the environment (OECD, 1993). Subsequently, an additional OECD work group concurred that PLC have "insignificant environmental health and human health impacts" (OECD, 2009). In addition, the European Commission commissioned a report (BIO by Deloitte, 2015) wherein several member countries agreed on the polymer properties predictive of adverse human health and environmental hazard. The report outlined eligibility criteria for a polymer to be considered a PLC. In 2019, the industry-led European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC) developed a "Conceptual Framework for Polymer Risk Assessment" ("CF4Polymers"; ECETOC, 2019). CF4Polymers provides guiding elements to be considered in assessing potential ecological and human health hazards and risks posed by polymer substances. CF4Polymers also considers specific life-cycle stages of polymer products and their associated routes of exposure. The authors of the CF4Polymers framework support the PLC approach as a means to accomplish polymer risk assessments. They specifically support the findings of Henry et al. (2018) and state that they are "…unaware of scientific evidence to justify generally assigning fluoropolymers the same level of regulatory concern as other PFAS" (ECETOC, 2019). In 2020, the European Commission contracted a study to propose criteria for the identification of polymers requiring registration (PRR) under REACH (Wood, 2020a). The Wood report states that the authors consider that fluoropolymers meet the criteria to be considered PLC, "following the recommendations of Henry et al." Considerable debate and comment on proposals have been put forward as the process and discussion advances (American Chamber of Commerce in Europe [Amcham], 2020b; FPG, 2021a; Hafer, 2021).

Four major fluoropolymers have previously been demonstrated to meet the criteria as PLC (Henry et al., 2018). This 2018 study raised interest in gathering similar data for additional commercial fluoropolymer products, both in scope and polymer type. In this study, seven global fluoropolymer manufacturers from the USA, Europe, and Asia collaborated to gather and present data for 14 additional fluoropolymers. In addition to information describing chemical composition, uses, performance properties, and functionalities of the 14 fluoropolymers, author company data for each of the PLC criteria are presented and discussed. The results demonstrate that each of the 14 commercially manufactured fluoropolymers in this study satisfy the widely accepted assessment criteria to be considered PLC and merit such designation. The study results add further evidence to demonstrate that fluoropolymers are demonstrably different and should not be grouped with other PFAS for hazard assessment or regulatory purposes.

USES, PERFORMANCE PROPERTIES, AND FUNCTIONALITY OF FLUOROPLASTICS AND FLUOROELASTOMERS IN THIS STUDY

The fluoropolymers described and evaluated in this study are high-performance materials used in commercial and industrial applications. Described herein are the industries and sectors (Table 1) and the performance properties and functionalities (Table 2) of the study fluoropolymers. The unparalleled combination of properties makes fluoropolymers critical materials for a broad range of applications and industrial sectors including automotive, aerospace, energy production and storage, and electronics (Table 1). Fluoropolymers are an important driver of the European Green Deal (FPG, 2021a) and UN Sustainability Development Goals (United Nations [UN], 2021), supporting smart mobility, clean energy, and sustainable industry. They are used in various components of renewable energy installations, such as hydrogen and photovoltaic panels and facilitate advanced energy storage and conversion technologies such as lithium-ion batteries (FPG, 2021a). Fluoropolymers are (i) durable, stable, and mechanically strong in harsh conditions; (ii) chemically inert, meeting the requirements for low levels of contaminants and particulates in manufacturing environments that are critical to the food and beverage, pharmaceutical, medical, and semiconductor industries; and (iii) biocompatible, nonwetting, nonstick, and highly resistant to

TABLE 1 Fluoropolymer end uses and industries

Industries	Transportation		Health care		Chemical		Consumer			Telecommunications		Textiles	Infra-structure	Renewable energy		
End uses	Automotive	Aerospace	Pharma-ceuticals	Medical devices	Oil and gas	Chemical process industry (CPI)	Production of goods	Protection and packaging	Filtration	Electronics and semicon-ductors	Internet and wireless communica-tions	Technical textiles	Construc-tion and archi-tecture	Energy production	Hydrogen production	Energy storage
Fluoroplastics																
PVDF homopolymer	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
PVDF copolymer	•	•	•	•		•	•	•	•	•	•	•	•		•	•
ECTFE copolymer	•	•	•		•	•				•	•		•			
ECTFE terpolymer			•		•	•										
PCTFE		•	•							•						
FEVE	•	•								•			•			
EFEP	•			•		•				•						
CPT	•									•						
THV	•	•	•			•	•	•	•	•			•	•		•
Fluoroelastomers																
FEPM	•	•	•	•	•	•	•			•			•	•		
FKM	•	•	•	•	•	•	•	•		•		•	•	•	•	•
FFKM		•	•	•	•	•	•			•						
Specialty																
Amorphous		•	•	•		•				•	•				•	•
Ionomer	•			•		•			•	•				•	•	•

Note: See also Chapter 5 in the Supporting Information.
Abbreviations: CPT, chlorotrifluoroethylene-tetrafluoroethylene; ECTFE, ethylene-chlorotrifluoroethylene; EFEP, ethylene-tetrafluoroethylene-hexafluoropropylene; FEPM, trifluoroethylene-propylene copolymer; FEVE, fluoroethylene-vinyl ether; FKM, HFP-VF2 polymer and HFP-VF2-TFE polymers; FFKM, TFE-PMVE perfluoroelastomer; PCTFE, polychlorotrifluoroethylene; PVDF, polyvinylidene fluoride; THV, TFE-HFP-VF2.

DOI: 10.1002/ieam.4646

TABLE 2 Fluoropolymer properties and functionality

	Durable				Inert—Stable				
See Supporting Information: Chapter 2 for property descriptions	Mechanical strength	Wear resistance	Flexibility	Low coefficient of friction	Resistance to chemicals	Weatherability	Cryogenic properties (lower than −50 °C)	High operating temperature range	High limiting oxygen index
Fluoroplastics									
PVDF Homopolymer	•	•		•	•	•		•	•
PVDF Copolymer	•	•		•	•	•		•	•
ECTFE Copolymer	•	•		•	•	•	•	•	•
ECTFE Terpolymer		•		•	•	•		•	•
PCTFE	•	•		•	•	•	•	•	•
FEVE	•	•	•	•	•	•		•	•
EFEP	•	•		•	•	•	•	•	•
CPT				•	•	•	•	•	•
THV			•		•	•		•	•
Fluoroelastomers									
FEPM	•	•	•		•	•		•	•
FKM	•	•	•		•	•		•	•
FFKM	•	•	•		•			•	•
Specialty									
Amorphous			•	•	•			•	•
Ionomer			•		•				•

	Functional								
See Supporting Information: Chapter 2 for property descriptions	Electrical insulator—high data transmission rate	Ionic conductivity	Piezo-electrical properties	Barrier properties	Nonstick properties	Ultra high purity grades for clean applications	Optical clarity	Low refractive index—used for optical effects	Polymer processing additive (PPA)[a]
Fluoroplastics									
PVDF Homopolymer			•	•		•		•	•
PVDF Copolymer			•	•				•	•

(*Continued*)

TABLE 2 (*Continued*)

	Functional								
See Supporting Information: Chapter 2 for property descriptions	Electrical insulator—high data transmission rate	Ionic conductivity	Piezo-electrical properties	Barrier properties	Nonstick properties	Ultra high purity grades for clean applications	Optical clarity	Low refractive index—used for optical effects	Polymer processing additive (PPA)[a]
ECTFE Copolymer	•			•					
ECTFE Terpolymer				•					
PCTFE				•	•	•	•	•	
FEVE				•			•		
EFEP				•	•		•	•	•
CPT				•	•	•	•	•	
THV				•			•	•	•
Fluoroelastomers									
FEPM	•			•					
FKM				•	•				•
FFKM	•			•		•			
Specialty									
Amorphous	•	•		•	•	•	•	•	
Ionomer	•	•		•			•		

Note: See Chapter 5 in the Supporting Information.

Abbreviations: CPT, chlorotrifluoroethylene-tetrafluoroethylene; ECTFE, ethylene-chlorotrifluoroethylene; EFEP, ethylene-tetrafluoroethylene-hexafluoropropylene; FEPM, trifluoroethylene-propylene copolymer; FEVE, fluoroethylene-vinyl ether; FKM, HFP-VF2 polymer and HFP-VF2-TFE polymers; FFKM, TFE-PMVE perfluoroelastomer; PCTFE, polychlorotrifluoroethylene; PVDF, polyvinylidene fluoride; THV, TFE-HFP-VF2.

[a] Polymer Processing Additives (PPA): also known as Polymer Processing Aid, Extrusion Process Aids or Polymer Processing and Recycling Aids.

temperature, fire, and weather (Table 2). Fluoropolymers are the preferred choice of material because of their unique combination of properties that are not achievable from other materials or via other functions. As a result, fluoropolymers have become a critical mainstay for our society providing vital, reliable functionality to a broad range of industrial and consumer products.

Three fluoropolymer types are included in this study: fluoroplastics, fluoroelastomers, and specialty fluoroplastics. Here, we describe briefly each included in this study. Additional details about each polymer are provided in the Supporting Information: Chapter 5.

Fluoroplastics

The fluoroplastics included in this study are: polyvinylidene fluoride (PVDF) homopolymer, PVDF copolymer, ethylene-chlorotrifluoroethylene (ECTFE) copolymer, ECTFE terpolymer, polychlorotrifluoroethylene (PCTFE), fluoroethylene-vinyl ether (FEVE), ethylene-tetrafluoroethylene-hexafluoropropylene (EFEP) terpolymer, chlorotrifluoroethylene-tetrafluoroethylene (CPT) terpolymer, and tetrafluoroethylene, hexafluoropropylene, vinylidene fluoride (TFE-HFP-VF2 [THV]) terpolymer as well as the specialty fluoroplastics, amorphous fluoropolymers, and fluorinated ionomers. Typical monomers used in the manufacture of fluoroplastics include tetrafluoroethylene (TFE), hexafluoropropylene (HFP), vinylidene fluoride (VDF or VF2), chlorotrifluoroethylene (CTFE), vinyl fluoride (VF), trifluoroethylene (TrFE), and perfluoroalkyl vinyl ethers (PAVEs), which include trifluoromethyl trifluorovinyl ether (PMVE), pentafluoroethyl trifluorovinyl ether (PEVE), and heptafluoropropyl trifluorovinyl ether (PPVE). In some copolymers, monomers that do not contain fluorine attached to the olefinic carbons may be used. These include ethylene, propylene, perfluoroalkyl-substituted ethylenes, and others (Ebnesajjad, 2000, 2003; Grot, 2011).

Fluoroelastomers

The fluoroelastomers included in this study are: trifluoroethylene-propylene copolymer (FEPM), HFP-VF2 polymer and HFP-VF2-TFE polymers (FKM), and TFE-PMVE perfluoroelastomer (FFKM). Typical monomers used in the manufacture of fluoroelastomers include VDF, HFP, TFE, CTFE, PAVEs, as well as propylene, 1-hydropentafluoropropene (HPFP), and 2,3,3,3-tetrafluoropropene (HFO-1234yf; FPG, 2021a). Although fluoroelastomers are based on many of the monomers that are also used for the synthesis of fluoroplastics, they are different because of the specific composition, flexibility with subambient glass transition temperatures, as well as their elastomeric properties, resulting from the cross-linking process. Cross-linking, known as curing or vulcanizing, is a hardening process to form chemical bonds between polymer chains that gives polymers their elasticity (Améduri et al., 2001; Drobny, 2016).

PVDF homo- and copolymers

Polyvinylidene fluoride fluoropolymers are specified by end users across the world for their outstanding combination of properties. Because they have high temperature resistance, low permeability, and high mechanical strength, and provide chemical resistance to a wide range of aggressive chemicals, PVDF fluoropolymers are used as a contact surface for the production, storage, and transfer of corrosive fluids (chemically resistant to halogens and acids) in the chemical processing industry, oil and gas transportation, and cables industry (Arkema, 2021a; Gujarat Fluorochemicals Limited, 2018, 2022; Solvay, 2021a). The outstanding resistance to sunlight/UV exposure make PVDF suitable for architectural coatings. The outdoor aging and weathering properties of PVDF resin led to its use in long-lasting paints for coating metal sheet for the past 50 years. PVDF resins can also be used to protect thermoplastics through coextrusion or film lamination techniques to obtain antigrime and antigraffiti surfaces with exceptional weathering properties. PVDF fluoropolymers also exhibit radiation resistance, desirable burn characteristics, flame, and smoke properties, easy processing on industry-standard equipment, and easy postprocessing steps, such as welding and fabrication. PVDF is used as a binder in lithium-ion batteries as well as PVDF film for solar power panels because of its high thermal and electrochemical stability, its stability under harsh environmental conditions, and its strong adhesion properties are critical to achieving environmental goals.

ECTFE (co- and terpolymers)

Ethylene chlorotrifluoroethylene (ECTFE) is a semicrystalline and melt-processable fluoropolymer obtained by the copolymerization of the two monomers, ethylene and chlorotrifluoroethylene, with an essentially 1:1 alternating structure (Ebnesajjad, 2017). Due to its chemical structure, ECTFE offers a unique combination of properties including chemical resistance, high thermal rating, and very good mechanical properties (Solvay, 2021b). ECTFE terpolymer with added hexafluoroisobutylene monomer displays enhanced stress-cracking performances resulting from chain-structure modifications of the polymer. ECTFE is used widely in anticorrosion applications such as coatings or in self-supporting construction (pipes) and architectural films (Solvay, 2021c). One of the principal advantages of ECTFE fluoropolymer is the ease with which it can be processed. It is a true thermoplastic that can be handled by conventional techniques of extrusion as well as by blow, compression, injection, rotational, and transfer molding. Powder coating methods are also applicable. ECTFE embodies an exemplary trade-off among general properties, offering high chemical and mechanical resistance combined with easy processing of the resin.

PCTFE

Polychlorotrifluoroethylene is a homopolymer of chlorotrifluoroethylene. PCTFE is melt processable and can be extruded or molded (Satokawa, 1990). PCTFE has outstanding mechanical properties, especially hardness, and chemical resistance compared with PTFE and PFA, although it is slightly inferior to PFA and FEP in heat resistance and chemical resistance (Daikin, 2021a; Satokawa, 1990). PCTFE has been applied widely in the semiconductor industries and aerospace industries (Curbell, 2021; Daikin, 2021a). In addition to distinguished thermal and chemical stability, it has very low moisture absorption and permeation; therefore, PCTFE is used in pharmaceutical packaging (Honeywell, 2021).

FEVE

Fluoroethylene-vinyl ether fluoropolymer resins are manufactured by copolymerization of fluoroethylene monomer and a vinyl ether monomer and consist of alternating fluoroethylene and alkyl vinyl ether segments (AGC Chemicals Company, 2021a; Parker & Blankenship, 2015). They were developed in 1982 as the first solvent-soluble fluoropolymers in the world (Darden & Parker, 2021; Kojima & Yamabe, 1984; Munekata, 1988; Yamabe et al., 1984). The alternating fluorinated segments provide outstanding UV stability, weather resistance, and chemical resistance, while the vinyl ether segments provide solvent compatibility and cross-linking sites (Parker & Blankenship, 2015; Scheirs, 2007). FEVE resins are used to make ultra-weatherable coatings for architectural, aerospace, automotive, bridge, and industrial maintenance markets (Hoshino & Morizawa, 2017).

EFEP

Ethylene-tetrafluoroethylene-hexafluoropropylene is a terpolymer of ethylene, tetrafluoroethylene, and hexafluoropropylene. It was designed to have many of the properties of ETFE. It has a lower processing temperature, which allows it to be coextruded with conventional thermoplastic polymers such as polyamide, ethylene vinyl alcohol (EVOH), and modified polyethylene. EFEP can be extruded, injection molded, and blow molded, and it is used in many applications such as those identified in Supporting Information: Chapter 4.7 (Daikin, 2011a). EFEP is a melt-processable resin with good processability because of its low melting point. It also has excellent mechanical properties, provides chemical resistance, low permeability, exceptional weatherability, and good heat resistance. Other prominent features include inherent flame retardancy as well as good optical properties given that EFEP is highly transparent and has both a low dielectric constant and loss tangent.

CPT

Chlorotrifluoroethylene-tetrafluoroethylene is a terpolymer of chlorotrifluoroethylene, tetrafluoroethylene, and perfluoroalkyl-vinyl-ether. It is a melt-processable polymer and resin, which is readily processed because of its lower melting point. It can be melt-molded as a thermoplastic resin by extrusion, injection, and compression molding. CPT is a modified perfluoroalkoxy fluoropolymer (PFA), which utilizes chlorotrifluoroethylene to provide low permeability to PFA, and it has many outstanding properties as a hybrid polymer of PFA and PCTFE as shown below. It has demonstrated permeation resistance to organic solvent, chemicals, water vapor, and gasoline (Daikin, 2011b). CPT offers superior permeation resistance against gasoline and flexible fuel and can be part of construction meeting the LEV III requirements (US environmental protection regulations in this automotive application). CPT also has notable barrier properties against many kinds of organic solvents and strong acids, especially HF, HCl, and HNO_3. This is very useful for semiconductor applications (Daikin, 2021b). In addition to the features noted above, CPT also provides heat resistance, excellent weatherability, flame retardancy, and good optical properties owing to its high transparency.

THV

THV fluoropolymers are a group of fluorinated thermoplastic polymers composed mainly of tetrafluoroethylene (TFE), hexafluoropropylene (HFP), and vinylidene fluoride (VDF; Domininghaus, 1998; Hintzer & Schwertfeger, 2014; Hull et al., 1997). The melting point of the different grades ranges from approximately 100 °C to nearly 250 °C. THV fluoropolymers are easy to process due to their broad processing windows. Different THV grades exhibit high flexibility, high transparency, bondability to fluorinated and nonfluorinated materials, and very good permeation resistance against fuels and other chemicals. The polymers are used as a barrier layer in fuel hoses, for transparent films and tubing, as matrix materials in composites, and the bonding layer in multilayer construction (Dams & Hintzer, 2017; Hull et al., 1997). The high transparency of the special film makes it an ideal adhesive film for laminated glass and the optimal protective film for surfaces. THV grades compete against other fluorothermoplastic materials for applications that require transparency and low refractive index as well as with fuel barrier materials. Commercial nonfluorinated materials cannot be used as substitutes for THV because of the unique combination of properties. Polymethylmethacrylate (PMMA) is used in conjunction with THV to provide differences in refractive index to create the total reflection needed for polymer optical fibers (Park et al., 2008). Transparent polymers, such as PMMA or polycarbonate, do not have the same chemical resistance or UV resistance to compete directly with THV.

FEPM

Trifluoroethylene-propylene copolymer elastomers, ASTM D1418, are high MW fluoropolymers with alternating tetrafluoroethylene and propylene segments (Kojima et al., 1977). They are also known as TFE-P copolymers. Various articles can be produced by means of compression molding, extrusion, injection molding, and calendering. FEPM elastomers are compounded and cured (cross-linked) to deliver unique and valuable properties by providing exceptional heat resistance with a continuous service temperature higher than

200 °C, outstanding chemical resistance with little or no deterioration even in contact with strong acids, bases, and oxidants at high temperatures, steam resistance, and high electrical resistivity on the order of 10^{15}–10^{16} Ω/cm (bulk resistivity). Formulated FEPM components are now used worldwide in many critical industrial applications where they must function safely in harsh environments, thereby extending the life of critical components and reducing downtime and costly repairs. FEPM elastomers are used in a range of applications including thermal power plants, oil and gas industry, ocean development, chemical and nuclear plants, automotive, aerospace, heavy-duty diesel, electronics, machinery, renewable energy, food processing, and medical. Their noted heat and chemical resistance make them especially valuable in oil and gas extraction (downhole) applications, where reliability is essential to cost effective and environmentally responsible production (Hull, 1983). FEPM elastomers are also used in high-performance wire and cable applications as insulating materials with the highest heat resistance, for example, lightweight, high-voltage automotive cables and motor cables for Japanese high-speed bullet trains (AGC Chemicals Company, 2021b).

Fluoroelastomers (FKM)

FKM are a family of fluoroelastomer materials defined by ASTM international standard D1418 (ASTM, 2021). FKM fluoroelastomers contain vinylidene fluoride (VDF) as a monomer combined with a variety of other fluoromonomers to create a palette of polymers with properties tailored for specific uses (Dams & Hintzer, 2017; Drobny, 2016; Van Cleeff, 1997; Worm & Grootaert, 2001). Cross-linked FKM fluoroelastomers are amorphous polymers designed for demanding service applications in hostile environments characterized by broad operating temperature ranges in contact with industrial chemicals, oils, or fuels (Worm & Grootaert, 2001). FKM fluoroelastomers are used mainly in fabricated parts (e.g., o-rings, gaskets, seals) to provide barriers against a wide range of fluids under severe service conditions (Drobny, 2016). Their design allows stable extrusion and molding processes and fitting in a wide range of processing constraints, reducing the risk of failure and increasing productivity. FKM fluoroelastomers provide high temperature and aggressive fluids resistance and retention of properties over a wide and demanding range of operating use conditions (high and low temperatures) for sealing and fluid transport applications, offering far superior performance than hydrocarbon elastomers. Applications include aerospace, automotive, oil and gas, chemical processing, electrical, office equipment, food, pharmaceuticals, and consumer wearables. Additionally, uncured FKM fluoroelastomers are used as a polymer processing additive (PPA) or polymer extrusion aids in small amounts (50–2000 ppm) dispersed in polyolefins such as high-density polyethylene (HDPE) and linear low-density polyethylene (LLDPE), significantly improving their film extrusion characteristics, reducing melt fracture and die build-up, as well as increasing productivity, minimizing energy and water footprint, and enabling the extrusion of thin films (Lavallée, 2020; Shell, 2020).

FFKM

Perfluoroelastomers, designated by ASTM D1418 as FFKM, are a fully fluorinated class of elastomers that are typically made up of tetrafluoroethylene (TFE), a perfluoro (alkyl vinyl ether; PAVE), and a cure site monomer(s) (Ohkura & Morizawa, 2017). FFKM elastomers offer superior chemical and temperature resistance, excellent resistance to gas and liquid permeation, and resistance to weather and ozone with operating temperatures ranging from −40 °C to 325 °C (Drobny, 2016; Greene-Tweed, 2021a, 2021b). These polymers can also be compounded to meet the special requirements of upstream, midstream, and downstream oil and gas exploration due to their superior properties (Barnwell, 2021; Daemar, 2021). Because of these properties, FFKM elastomers are used in a wide variety of applications such as critical sealing solutions for the aerospace, pharmaceutical, medical, chemical processing, semiconductor, and oilfield industries (Atkinson, 2018; Marshall, 2017).

Amorphous fluoropolymers

Amorphous fluoropolymers are copolymers of TFE and specialty monomers that yield linear, high molar mass noncrystalline polymers (AGC Chemicals Company, 2021c; Gangal & Brothers, 2010; Hintzer et al., 2013; Korinek, 1994; Resnick & Buck, 1997, 1999). Amorphous fluoropolymers have the outstanding chemical and thermal stability and surface properties of semicrystalline perfluoropolymers as well as the unique properties associated with amorphous materials such as optical clarity and high gas permeability. The optical properties are outstanding, with more than 90% transmission, and thereby low dissipation, over a wide range of wavelengths (e.g., 200–2000 nm). TFE/PDD (2,2-bistrifluoromethyl-4,5-difluoro-1,3-dioxole) copolymers have the lowest refractive index known for a solid organic polymer (Groh & Zimmermann, 1991). This unique combination of properties makes amorphous fluoropolymers unmatched for uses in degassing, fiber optics, photolithography, antireflective coatings, passivation and protective coatings for medical, military, and aerospace devices, as well as electronic applications (Gangal & Brothers, 2010; Hintzer et al., 2013).

Fluorinated ionomers

Fluorinated ionomers are copolymers of TFE and a perfluorovinylether monomer containing an ionic group, typically a sulfonic acid or carboxylic acid (Grot, 2011, 2013). Fluorinated ionomers can be extruded or cast into film and converted into ion exchange materials (IXMs). IXMs come in a variety of useful forms offering a broad range of solutions for different applications (AGC Chemicals Company, 2021d; Asahi-Kasei, 2021; Chemours, 2021a). These forms include ion exchange membranes (IEMs), dispersions, and resins. IEMs must possess the required ion transport properties for the electrochemical cell in which they reside to perform well and work effectively. Some of these properties include high ionic conductivity, chemical resistance, high operating temperature range, low permeability, and balanced durability and performance (Chemours, 2021b).

Ion exchange membranes (IEMs) stand to play a noteworthy role in today's modern world (Chemours, 2021b) and as such, are utilized in a wide range of applications and end-use industries including electrochemical processing, energy production, and hydrogen production. IEMs revolutionized the chlor-alkali industry (Grot, 2013), the manufacture of primarily caustic soda and chlorine, by eliminating the use of hazardous materials such as mercury and asbestos (Asahi-Kasei, 2021) and, in doing so, reducing energy consumption. Water electrolysis, the process of converting water into hydrogen and oxygen, relies on IEM technology. Although this process requires electricity, renewable energy sources such as solar or wind power can be utilized, allowing the potential for hydrogen to be a "clean" energy source (Science Center, 2021). Hydrogen fuel cells, some of which use a type of IEM known as a proton exchange membrane, can then convert hydrogen to electricity, a crucial technology to reach the stated target of the EU New Green Deal (EC, 2021).

STUDY METHODOLOGY AND DATA

Seven global fluoropolymer manufacturers (AGC Chemicals Americas, Arkema, The Chemours Company, Daikin Industries, Gujarat Fluorochemicals Limited, Solvay Specialty Polymers, and 3M Company) participated in this study and contributed data, writing, critique, and analysis. The companies noted above are members of the US-based Performance Fluoropolymer Partnership (PFP) and/or EU-based Fluoropolymer Product Group (FPG).

This study provides data on 14 fluoropolymers, building on a prior study (Henry et al., 2018). The study was chartered within two global industry groups. Participants put forward candidate fluoropolymers of notable commercial importance for the study and provided company and published data that address the PLC criteria. Thirteen PLC criteria that relate to the polymer structure and properties, including three to physicochemical properties and five to stability, set forth in BIO by Deloitte (2015) and presented in prior work on four fluoropolymers (Henry et al., 2018), are addressed in this study (Figure 1). These criteria are briefly described in Table 3 with further description provided in Supporting Information: Chapter 3 and in the prior work (Henry et al., 2018). Participants provided company and published data and a description of methods and/or public references to demonstrate the origin of the data provided. These methods and references are provided in detail in Supporting Information: Chapter 4. The PLC criteria data were compiled and are presented in Tables 4 and 5.

The data assessment was done in two ways: Companies could self-assess the PLC data if they had the technical resources to do so or they could submit their PLC data to a third-party contractor for an independent technical review. The third-party consultant hired by PFP was GSI Environmental Inc. The objective was to be able to publish the references and methods behind the PLC data provided for each fluoropolymer in the study. In cases where the data and/or methods contained confidential business information, the third-party consultant independently evaluated the information supplied before it was shared in a blinded, aggregate form with the participating project companies. In several cases—FKM, PVDF, and ionomers—several companies submitted data for the same fluoropolymer. The data were combined and are presented in Tables 4 and 5. There is no intentional company attribution for the data presented.

The following describes further how the study data were generated and compiled.

- A third-party consulting company (GSI) was engaged to comment independently on data, methods, and references initially supplied by study participants for their respective fluoropolymers. Several study participants used this third-party consultant.
- Following the initial third-party assessment and assembly of the master data Tables 4 and 5 as well as the FKM data in Supporting Information: Table 4.11, a series of subsequent assessments were conducted (within PFP)

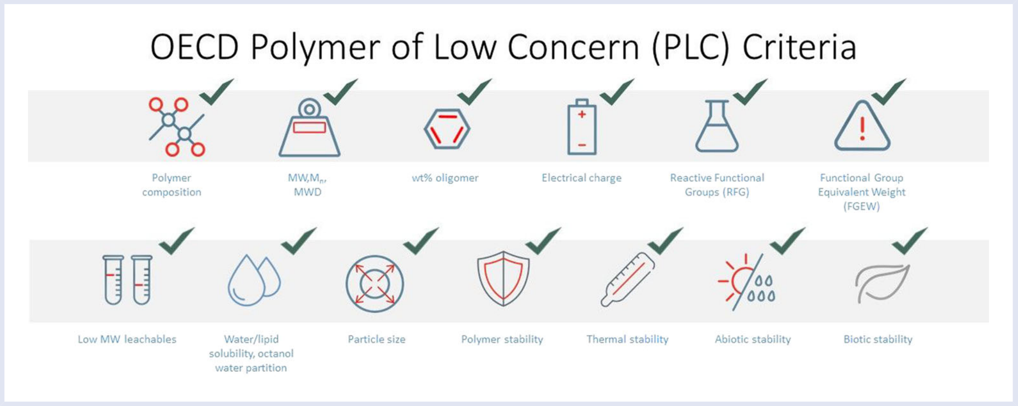


FIGURE 1 OECD polymer of low concern (PLC) criteria add (C) 2021 W.L.Gore & Associates

TABLE 3 Polymer of low concern (PLC) criteria descriptions

(See Supporting Information: Chapter 3 for additional details) Criterion	Description
Polymer composition	The polymer composition criterion requires structure and elemental composition of the polymer be described and identified (e.g., by Chemical Abstracts Service [CAS] number).
Molecular weight, number average molecular weight, MW distribution, and % oligomer <1000 Da	The number average molecular weight (Mn) and oligomer content are the most commonly used criteria for PLC assessment. The EU assessment report (BIO by Deloitte, 2015) states that the "most potential health concern polymers have a number average molecular weight, Mn, <1000 Da and oligomer content >1%." The higher the oligomeric content, the more likely a polymer is to be a health or ecotoxicological (OECD, 2009, p. 9).
	Molecular weight (MW) is an important predictor of biological effect because large molecules (>1000–10 000 Da) are too large to penetrate cell membranes (Supporting Information: in Beyer, 1993, p. 14). Because large molecular weight polymers cannot enter the cell, they cannot react with "target organs," such as the reproductive system, and are not bioavailable. "Therefore, as the Mn of a polymer increases, a reduced incidence of potential health concern effects might be expected" (OECD, 2009, p. 20).
	An additional PLC consideration is the weight percentage of oligomers that are <1000 Da. Oligomers may be composed of, for example, dimers, trimers, and tetramers, meaning they have 2- monomer, 3- monomer, and 4-monomer units, respectively. The EU report (BIO by Deloitte, 2015) concluded that most potential health concern polymers have Mn of <1000 Da and oligomer content of >1%: "…the distribution of potential health concern polymers exhibited an increased incidence of higher oligomer content that began at 5% for <1000 Da and 2% for <500 Da oligomeric content" (OECD, 2009, p. 24).
	Molecular weight distribution (MWD), also known as "polydispersity index," measures the heterogeneity of size of polymer molecules in a polymer. The MWD is an important parameter for predicting potential biological effects of polymers because, although Mn may be a large value, low MW oligomers <1000 Da may be present, which could penetrate the cell.
Ionic character	Electrical charge or ionic character can be anionic, cationic, amphoteric, or nonionic. Specifically, cationic polymers have been associated with aquatic toxicity (Auer et al., 1990; USEPA, 1997a).
Reactive functional groups and RFG ratio to MW	A "reactive functional group" (RFG) is defined as an atom or associated group of atoms in a chemical substance that is intended or can be reasonably expected to undergo facile chemical reaction (USFR, 2012). Some highly reactive functional groups (or a high ratio of RFGs per mole) have been associated with adverse human health and ecotoxicology (e.g., acrylates, methacrylates, isocyanates, anhydrides, aziridines; USEPA, 2010).
	The functional group equivalent weight (FGEW) is used to determine if the RFGs in a polymer are substantially diluted by polymeric material to allow the polymer to be a PLC (USEPA, 1997). The FGEW of a polymer is defined as the ratio of the Mn to the number of functional groups in the polymer. The FGEW is used as an indication of the degree of reactivity of the polymer; the lower the FGEW, the more reactive the polymer and the greater the potential for health and environmental impact (OECD, 2009, p. 10).
Low MW leachables	Low MW leachables are chemical molecules, either inorganic or organic, that migrate (i.e., leach) out of the polymer. These could be residual monomers or oligomers resulting from incomplete polymerization processes, surface residues, or other chemicals used in the manufacturing processes (e.g., initiators, catalysts, chain transfer agents, surfactants).
	Low MW leachables are critically important to the potential for a polymer to affect health and the environment, given that they may be able to migrate out of the polymer and cross cell membranes to potentially react with biomolecules. A report to the EU (BIO by Deloitte, 2015) concluded that "Polymers with <1% MW < 1000 Da and low water extractability are not able to cause systemic effects which are toxicologically or ecotoxicologically relevant."
	Monomers, by nature, are reactive. Unreacted monomers left in a polymer may migrate out of the polymer to react with biomolecules to cause potential adverse effects. Regulatory authorities (BIO by Deloitte, 2015) and the OECD Expert Group on Polymers (OECD, 2009) agree that the residual monomer content of a polymer is critical to determining if it qualifies as a PLC.

(*Continued*)

TABLE 3 (*Continued*)

(See Supporting Information: Chapter 3 for additional details) Criterion	Description
Particle size	Particle size is also a PLC criterion. Particles that are small enough to reach the deep lung upon inhalation are often associated with adverse health effects. Therefore, to qualify as a PLC, median mass aerodynamic diameter (MMAD) of the polymer particle size should be >5 µm.
Structural and elemental composition	In the US, Chemical Categories of Concern are the result of the review of new chemicals by the USEPA under the TSCA (see https://www.epa.gov/reviewing-new-chemicals-under-toxic-substances-control-act-tsca/chemical-categories-used-review-new). The categories describe the molecular structure, boundary conditions such as MW, equivalent weight, the log of the octanol–water partition coefficient, log *P*, or water solubility, and standard hazard (mammalian and ecological) and (environmental) fate tests to address concerns.
Elemental composition	The elemental composition is a factor in the assessment of the eligibility of polymers for reduced notification requirements. The exclusion of polymers under this step is not a conclusion of hazard but a determination that the elemental composition does not fall within the parameters of the polymer set under which this rule was formulated, and consequently, these polymers would have to follow the standard notification and review process. These elemental requirements differ across jurisdictions as covered in the report to the EU on global regulatory approaches to polymer assessment (BIO by Deloitte, 2015). For example, in the EU under REACH it is proposed that polymers composed from among these elements, covalently bound to C, have reduced hazard: H, N, O, Si, S, F, Cl, Br, or I (BIO by Deloitte, 2015). In contrast, the USEPA Polymer Exemption Rule states that a polymer is eligible for reduced agency review when it has at least two of the following elements: C, H, O, N, S, or Si (USFR, 1995).
Water and lipid solubility and the octanol–water partition coefficient	Water solubility is the extent to which a compound will dissolve in water. According to the OECD (2009) meeting of the Expert Group on Polymers, polymers with “negligible” water solubility, or those described as “hydrophobic” have been represented with a water solubility of 0.000001 mg/L (1×10^{-6} mg/L; assigned arbitrarily; OECD, 2009). That is equivalent to 1 ppt, a very conservative definition.
	Polymers with water solubility <10 mg/L showed generally low health concerns.
	The octanol–water partition coefficient (K_{ow}) is another criterion to assess chemicals and their environmental and health impact. The K_{ow} is a physical–chemical property at equilibrium to represent the lipophilic or hydrophilic nature of a chemical, the distribution of a compound in octanol, representing the lipophilic nature, to its solubility in water, representing the aqueous nature. The higher the K_{ow}, the more lipophilic the compound. Typically, a K_{ow} >5000 or a log K_{ow} >5 means high lipophilicity and, thus, a high potential to bioaccumulate or bioconcentrate. According to the Stockholm Convention, a bioconcentration factor of >5000 and a log K_{ow} >5 is used as a criterion for bioaccumulation.
Stability	Stability is resistance to physical, chemical, or biological transformation. Loss of stability in the polymer breaks it down into smaller pieces, producing low MW species. As was previously described in the Polymer of Low Concern section under the molecular weight, number average molecular weight, MW distribution, and % oligomer <1000 Da heading, molecules with Mn <1000 Da are capable of crossing cell membranes, making unstable polymers potentially hazardous to health and the environment.
Abiotic stability	Polymers are stable; monomers are not. Abiotic degradation may involve sunlight, water, or oxygen. Photochemical transformation is a reaction involving the radiation energy of sunlight (ultraviolet radiation) that may break a bond in a molecule to change it to another chemical entity. Hydrolytic degradation of polymers is another potential way to break the polymer bonds, creating smaller oligomers that may be bioavailable. Chemical oxidation is a reaction involving the loss of electrons from one atom to another.
Biotic stability: aerobic, anaerobic, and in vivo	Biotic stability is assessed by whether the polymer is degraded by microorganisms under oxygenated (aerobic) or anoxic (anaerobic) conditions; in vitro and in vivo stability studies demonstrate this. In vivo biodegradation involves the breaking of the polymer bonds by the action of bacteria, enzymes, and oxidants within the organism.
Thermal stability	Thermal stability of a polymer can be assessed when used as intended under normal, foreseeable use conditions or in extreme temperatures during disposal, such as by incineration. Thermal stability testing may involve Thermogravimetric Analysis (TGA), which determines mass loss over time and temperature of a test substance.

TABLE 4 Fluoroplastics and PLC criteria

	Fluoroplastics				
Supporting Information Data: Chapter	**4.1 PVDF**	**4.2 PVDF-HFP copolymer**	**4.3 ECTFE**	**4.4 ECTFE**	**4.5 PCTFE**
	Polyvinylidene fluoride	Vinylidene fluoride, hexafluoropropene copolymer	Ethylene, chlorotrifluoroethylene copolymer	Ethylene, chlorotrifluorethylene, hexafluoroisobutylene terpolymer	Polychlorotrifluoroethylene
PLC assessment criterion[a]	CAS 24937-79-9	CAS 9011-17-0	CAS 25101-45-5	CAS 54302-04-04	CAS 9002-83-9
Structure	$–(CF_2–CH_2)_n–$	$–(CF_2–CH_2)_n–[CF(CF_3)–CF_2]_m–$	$–(CF_2–CFCl–CH_2–CH_2)_n–$	$–(C_4H_2F_6)_n–(C_2H_4)_m–(C_2ClF_3)_i–$	$–(CF_2–CFCl)_n–$
Polymer composition (must have C, H, Si, S, F, Cl, Br, or I covalently bound to carbon)	Yes	Yes	Yes	Yes	Yes
Molecular weight (Mn)[b] (Mn >1000 Da and oligomer content <1%)	70 000–300 000	80 000–300 000	Mn >50 000	Mn >50 000	70 000–400 000 average based on grade type
Molecular weight distribution Mw[c] ÷ number average M_n	2–3	2–3	1.1	1.7	3
Wt% oligomer (<5% for <1000 Da oligomers, <2% for <500 Da oligomers)	Negligible	Negligible	Negligible	Negligible	Negligible
Ionic character	Neutral	Neutral	Neutral	Neutral	Neutral
Reactive functional groups (RFGs)[d] **and functional group equivalent weight (FGEW)**	None and N/A	None and N/A	None and N/A	None and N/A	None and N/A
Low molecular weight leachables	No active leachables by USP class VI (121 °C)	No active leachables by USP class VI (121 °C)	No active leachables by USP class VI (121 °C)	No active leachables by USP class VI (121 °C)	Negligible
Residual monomers	<50 ppb	<50 ppb	<50 ppb	<50 ppb	<0.1 wt%
Ratio of residual monomers to molecular weight (typical value)	$\sim10^{-12}$–$\sim10^{-13}$	$\sim10^{-12}$–$\sim10^{-14}$	$\sim10^{-13}$	$\sim10^{-13}$	$<10^{-5}$
Structural similarities to RFG of concern	None	None	None	None	None
Reference standard	ASTM D3222-18a	ASTM D5575-18	ASTM D3275-81	ASTM D3275-81	

(*Continued*)

Integr Environ Assess Manag 2023:326–354 DOI: 10.1002/ieam.4646

TABLE 4 (*Continued*)

	Fluoroplastics				
Supporting Information Data: Chapter	4.1 PVDF	4.2 PVDF-HFP copolymer	4.3 ECTFE	4.4 ECTFE	4.5 PCTFE
Physical–chemical properties					
Water solubility and octanol/ water partition coefficient, K_{ow}	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A
Particle size (median mass aerodynamic diameter, MMAD, should be >5 µm)	Powders: 5–300 µm pellets: 2–4 mm	Powders: 5–300 µm pellets: 2–4 mm	D50%: 50–70 µm (typical)	D50%: 50–70 µm (typical)	Pellet: 2-4 µm, flake: 0.54 mm powder: 5–300 micron
Stability					
Hydrolysis, light (hν), Oxidation, biodegradation (aerobic and anaerobic)	Stable	Stable	Stable	Stable	Stable
Thermal stability at normal foreseeable use maximum continuous temp. (°C)	150 °C	150 °C	150 °C	150 °C	120 °C
Meets [a]PLC criteria (Yes or No)	Yes	Yes	Yes	Yes	Yes
Fluorinated polymerization aid (PA) used? (Yes or No)	No	No	No	No	No
Recommended processing/ application (use) temperature (T°C)	Processing: 200 °C–250 °C Use max temp: 150 °C	Processing: 180 °C–250 °C Use max temp: 100 °C–140 °C depending on HFP content	Processing: 250 °C–280 °C Use max. Temp: 150 °C	Processing: 250 °C–280 °C Use max. Temp: 150 °C	Molding: 230 °C –330 °C and Use Max same as above at 120 °C

	Fluoroplastics			
Supporting Information Data: Chapter	4.6 FEVE	4.7 EFEP	4.8 CPT	4.9 THV
	Fluoroethylene-vinyl ether copolymer	1-Propene, 1,1,2,3,3,3-hexafluoro-, polymer with ethylene and 1,1,2,2-tetrafluoroethylene	1,1,1,2,2,3,3-Heptafluoro-3-[(trifluoroethenyl)oxy]propane polymer with chlorotrifluoroethylene and tetrafluoroethylene	1-Propene,1,1,2,3,3,3-hexafluoro-polymer with 1,1-difluoroethylene and tetrafluoroethylene
PLC assessment criterion[a]	cbi	35560-16-8	116018-07-6	25190-89-0

(*Continued*)

TABLE 4 (*Continued*)

	Fluoroplastics			
Supporting Information Data: Chapter	**4.6** **FEVE**	**4.7** **EFEP**	**4.8** **CPT**	**4.9** **THV**
Structure	cbi	$–(CH_2–CH_2)_n–(CF_2–CF_2)_m–[CF_2–CF(CF_3)]_l–$	$–(CF_2–CF_2)_n–(CFCl–CF_2)_m–[CF_2–CF(OR_f)]_l–$	$–(CF_2CH_2)_x–(CF_2–CF–CF_3)_y–(CF_2–CF_2)_z$
Polymer composition (must have C, H, Si, S, F, Cl, Br, or I covalently bound to carbon)	Yes	Yes	Yes	Yes
Molecular weight (Mn)[b] (Mn >1000 Da and oligomer content <1%)	7000–46 000	130 000	200 000–300 000	131 000
Molecular weight distribution Mw[c] ÷ number average M_n	2.0–4.0	4	2–5	1.8
Wt% oligomer (<5% for <1000 Da oligomers, <2% for <500 Da oligomers)	Mn <1000 range of <3.5% and Mn <500 is <0.7%	Negligible; <0.1 wt% oligomer content	Negligible; <0.1 wt% oligomer content	wt.% <1000: None
Ionic character	Neutral	Neutral	Neutral	Neutral
Reactive functional groups (RFGs)[d] **and functional group equivalent weight (FGEW)**	None and N/A	None and N/A	None and N/A	None and N/A
Low molecular weight leachables	Negligible; cross-linked as final product	Negligible	Negligible	No active leachables by USP class VI (121 °C)
Residual monomers	0.12%–1.43% non-fluorinated	Negligible	Negligible	None detected
Ratio of residual monomers to molecular weight (typical value)	$10^{-7}–10^{-8}$	$<10^{-5}$	$<10^{-5}$	$\sim 10^{-13}$
Structural similarities to RFG of concern	None	None	None	None
Reference standard		ASTM D7472	ASTM D7471	

(*Continued*)

TABLE 4 (*Continued*)

	Fluoroplastics			
Supporting Information Data: Chapter	4.6 FEVE	4.7 EFEP	4.8 CPT	4.9 THV
Physical–chemical properties				
Water solubility and octanol/ water partition coefficient, K_{ow}	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A
Particle size (median mass aerodynamic diameter, MMAD, should be >5 μm)	Solution or flake 150 nm for emulsion	2–4 mm (pellets)	2–4 mm (pellets)	Pellets ~400–750 μm
Stability				
Hydrolysis, light (hν), oxidation, biodegradation (aerobic and anaerobic)	Stable	Stable	Stable	Stable
Thermal stability at normal foreseeable use maximum continuous temp. (°C)	220 °C	130 °C; low melting point 160 °C–190 °C and high decomposiiton temperature of 357 °C–380 °C	200 °C; low melting point 239 °C–251 °C and high decomposition temperature of >400 °C	Continuous use is expected ~room T. (<100 °C as host resin melts at 120 °C); No expected degradation; fluoropolymer degrades >350 °C by TGA
Meets [a]PLC criteria (Yes or No)	Yes	Yes	Yes	Yes
Fluorinated polymerization aid (PA) used? (Yes or No)	No	No	No	Yes and No
Recommended processing/ application (use) temperature (T°C)	180 °C–200 °C	Molding temperature: 200 °C–280 °C; Use max as noted above	Molding temperature: 310 °C–330 °C; Use max as noted above	Melt processing: <350 °C Application: <100 °C (in LLDPE)

Abbreviations: ECTFE, ethylene-chlorotrifluoroethylene; HFP, hexafluoropropylene; PCTFE, polychlorotrifluoroethylene; PLC, polymer of low concern; PVDF, polyvinylidene fluoride.

[a] See OECD (2009) and BIO by Deloitte (2015) for details on characteristics of a "Polymer of Low Concern" and Supporting Information: Chapter 3.

[b] Molecular Weight is number average molecular weight which is defined as the total weight of the polymer divided by the total number of molecules. It is the mole fraction of molecules in a polymer sample.

[c] Molecular weight is weight average molecular weight which is determined by summing the weights of all the chians and then dividing by the total number of chains. It is the weight fraction of molecules in a polymer sample.

[d] For definition of reactive functional group, lists of low-, moderate-, and high-concern functional groups and FGEW limits, see USEPA polymer exemption guidance manual, BIO by Deloitte (2015, pp. 191–192), and USEPA (2010). See Supporting Information.

TABLE 5 Fluoroelastomers and specialty fluoroplastics—PLC criteria

	Specialty fluoroplastics		Fluoroelastomers		
Supporting Information Data: Chapter	4.13 Amorphous	4.14 Ionomer	4.10 FEPM	4.11 FKM	4.12 FFKM
	Perfluoro(alkenyl vinyl) ether polymer	Sodium or potassium salts of perfluorosulfonic acid/TFE copolymer or perfluorocarboxylic acid/TFE copolymer	Tetrafluoroethylene-propylene copolymer	1-Propene,1,1,2,3,3,3-hexafluoro-polymer with 1,1-difluoroethylene copolymer and terpolymers	Tetrafluoroethylene-trifluoromethyl trifluorovinyl ether copolymer
PLC assessment criterion[a]	37626-13-4	9002-84-0, 1314-23-4, 409-21-2, 111173-25-2	27029-05-6	9011-17-0, 26425-79-6, 25190-89-0	26425-79-6
Structure	See Supporting Information	See Supporting Information	See Supporting Information	Supporting Information	-(CF2CF2)x -[CF2-CF(OCF3)]y-(Cure Site Monomer)z
Polymer composition (must have C, H, Si, S, F, Cl, Br, or I covalently bound to carbon)	Yes	Yes	Yes	Yes	Yes
Molecular weight[b] (Mn >1000 Da and oligomer content <1%)	150 000–300 000	>100 000	Various grades vary between 146 000–275 000	30 000–340 000	10 000–1 000 000
Molecular weight distribution Mw[c] ÷ number average M_n	1.4–2.5	1.0–2.4	Various grades give various ratios from 1.4 to 3.3	1.2–2.4	1.2–3.5
Wt% oligomer (Figure MWD) (<5% for <1000 Da oligomers, <2% for <500 Da oligomers)	Negligible	Negligible	<0.01%	Negligible to <1%	Negligible
Ionic character	Neutral	Neutral	Neutral	Neutral	Neutral
Reactive functional groups (RFGs)[d]	None and N/A	None and N/A	None and N/A	None and N/A	None and N/A
Functional group equivalent weight (FGEW; typical value)	$>10^5$	$>10^5$	$>10^5$	$>10^4–10^5$	$>10^4$

(*Continued*)

DOI: 10.1002/ieam.4646

TABLE 5 (*Continued*)

	Specialty fluoroplastics		Fluoroelastomers		
Supporting Information Data: Chapter	4.13 Amorphous	4.14 Ionomer	4.10 FEPM	4.11 FKM	4.12 FFKM
Low molecular weight leachables	<1 ppm	<1 ppm	No active leachables	<0.4 ppm to <1 ppm	No active leachables
Residual monomers	<1 ppm	<1 ppm	No residual monomers Only cross-linking agent at <1 ppm	<50 ppt to <5 ppm	<50 ppb
Ratio of residual monomers to molecular weight (typical value)	$>10^{-5}$	$>10^{-5}$	10^{-11}–10^{-12}	$>10^{-10}$–10^{-13}	0.25 ppt as $Mn = 10^5$ (for representative FKM)
Structural similarities to RFG of concern	None	None	None	None	None
Reference standard				ASTM D 1418	
Physical–chemical properties					
Water solubility and octanol/water partition coefficient, K_{ow}	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A
Particle size (median mass aerodynamic diameter, aerodynamic diameter, MMAD, should be >5μm)	Solution, sheet or pellets	(1) Aqueous dispersion casting (as a film) followed by annealing or (2) Melt extrusion as a membrane (reinforced)	Sheet or crumb	Sheet or block; powders 300–350 μm stability increased/enhanced when cross-linked	Sheet or block; or “crumb”
Stability					
Hydrolysis, light (hν), oxidation, biodegradation (aerobic and anaerobic)	Stable	Stable	Stable	Stable	Stable

(*Continued*)

TABLE 5 (*Continued*)

	Specialty fluoroplastics		Fluoroelastomers		
Supporting Information Data: Chapter	4.13 Amorphous	4.14 Ionomer	4.10 FEPM	4.11 FKM	4.12 FFKM
Thermal stability at normal foreseeable use maximum continuous Temp (°C)	>250 °C	Sulfonic acid polymer: maximum operating temperature of 175 °C under anhydrous conditions, 220 °C –240 °C in aqueous systems carboxylic acid polymer: use below 120 °C	200 °C	180 °C	200 °C–300 °C
Meets[a] PLC criteria (Yes or No)	Yes	Yes	Yes	Yes	Yes
Fluorinated polymerization aid (PA) used? (Yes or No)	Yes and No	Yes and No	No	Yes and No	Yes and No
Recommended processing/ application (use) temperature (T°C)	<280 °C	Sulfonic acid polymer: maximum operating temperature of 175 °C under anhydrous conditions, 220 °C–240 °C in aqueous systems carboxylic acid polymer: use below 120 °C	−60 °C–204 °C (AFLAS Technical Document)	Melt processing: <300 °C 160 °C–320 °C (cross-linking temperature)	160 °C–320 °C (cross-linking temperature)

Abbreviations: FEPM, trifluoroethylene-propylene copolymer; FKM, HFP-VF2 polymer and HFP-VF2-TFE polymers; FFKM, TFE-PMVE perfluoroelastomer; PLC, polymer of low concern.

[a] See OECD (2009) and BIO by Deloitte (2015) for details on characteristics of a "Polymer of Low Concern."

[b] Molecular weight is *number* average molecular weight.

[c] Molecular weight is weight average molecular weight.

[d] For definition of reactive functional group, lists of low-, moderate-, and high-concern functional groups and FGEW limits, see USEPA polymer exemption guidance manual, BIO by Deloitte (2015, pp. 191–192), and USEPA (2010). See Supporting Information.

until all data cells in the tables cited above were backed up with a narrative, a testing method, and/or references where publicly available.

- Where several companies have provided data on the same fluoropolymers, the table data presented provide a multicompany compilation and assessment along with appropriate methods and references.
- Individual companies supplying data are identified as authors, but there is no direct attribution regarding which company supplied which data for this study.

PLC ASSESSMENT RESULTS

This study was conducted on commercial fluoropolymer products using the PLC criteria to characterize their potential hazard. Figure 1 illustrates the PLC criteria used (BIO by Deloitte, 2015; Henry et al., 2018). The pictured criteria encompass structure, physicochemical property, and stability criteria evaluated in the study. Data informing structure criteria, MW, Mn, and MW distribution (MWD), physicochemical property criteria, water and lipid solubility and K_{ow}, and stability criteria are presented in Tables 4 and 5. The study also gathered structural data on (a) residual monomers, (b) ratio of residual monomers to MW, (c) structural similarities to reactive functional groups (RFGs) of concern, and (d) thermal stability at normal foreseeable maximum continuous use temperatures. Brief descriptions of PLC criteria are provided in Table 3 with additional details, including references for each criterion in Supporting Information: Chapter 3. An additional data point gathered was whether the fluoropolymer(s) presented utilized a fluorinated polymerization aid (PA) during manufacture. The study results are presented in Tables 4 and 5 and summarized below.

Polymer composition: Each of the fluoroplastics, specialty fluoroplastics, and fluoroelastomers assessed in this study met the criterion of polymer composition whereby either fluorine (F) and/or chlorine (Cl) must be covalently bound to the carbon-only polymer backbone.

MW and MWD: All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the criteria for MW (Mn >1000 Da) and MWD (1–3). The data demonstrate the fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study are high-MW solid polymers with fairly narrow MWD and negligible to low wt% oligomer content. The MW for fluoroplastics in Table 4 and specialty fluoroplastics in Table 5 ranged from 50 000 to 300 000, and the MWD ranged from approximately 1.4 to 3. We note that FEVE was measured in its uncured state and that, upon curing, its MW increased significantly. The MW and MWD were determined in a variety of ways depending on the fluoropolymer and its solubility (or insolubility) in various solvents. The MW and MWD data for fluoroelastomers and specialty fluoroplastics in the study are presented in Table 5. The MW and MWD varied because of the various grades of fluoroelastomers ranging from 100 000 to 250 000 with some less than (down to 10 000) and greater than (up to 500 000). MWD was on the order of 1.4 to 3.5. Fluoroelastomer MW is lower for uncured fluoroelastomer versus cured fluoroelastomer. Cured fluoroelastomer is the form used in many formed-use applications (e.g., gaskets and o-rings). The methods and references for MW and MWD data are presented in the Supporting Information: Chapter 4 with the specific chapter noted in Tables 4 and 5. Methods included size exclusion chromatography (SEC), gel permeation chromatography (GPC) along with osmotic pressure, and parallel plate rheometry methods.

Weight % oligomer: The criteria for wt% oligomer are less than 5% oligomer content for Mn less than 1000 Da, and less than 2% oligomer content for Mn less than 500 Da (BIO by Deloitte, 2015; Henry et al., 2018; see also the Supporting Information). All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the wt% oligomer criteria. Many polymers in the study were reported as "negligible" for oligomers based on analyses conducted. Polymers in the study not cited as negligible have reported numerical data presented in Tables 4 and 5. In addition to SEC and GPC, analytical methods employed included a weight loss upon heating method and the FDA 21 CFR 177.1380 method. The methods and references for wt% oligomer are presented in the Supporting Information: Chapter 4 with the specific chapter noted in Tables 4 and 5.

Ionic character: The fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study are neutral polymers, either containing no ionic groups or may contain anionic at the terminus of their high MW polymer chains as noted in the prior study of fluoropolymers (Henry et al., 2018). Notably different are fluorinated ionomers, which have neutralized (salts) sulfonic acid or carboxylic acid groups pendant to the polymer backbone and as such are neutral and not ionically charged in their polymeric solid form and are low in toxicity and not dermally irritating on skin contact (USEPA, 1997). None of the evaluated polymers in the study have cationic nature. The methods and references for ionic character are presented in the Supporting Information: Chapter 4 with the specific subchapter noted in Tables 4 and 5.

RFG, functional group equivalent weight (FGEW) and structural similarities to RFG of concern: All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the RFG and FGEW criteria. The polymers in this study do not contain the reactive functional groups set forth in the PLC criteria (e.g., acrylates, alkoxysilanes, amines, aziridines, carbodiimides, and so forth; see Supporting Information: Chapter 3). Given that the polymers in this study have no RFGs, the FGEW values in Tables 4 and 5 are very large numbers (such as $>10^4$–10^5) or the value given is not applicable due to the lack of RFGs altogether. Even the polymers with some functional groups present (e.g., fluorinated ionomers) are not reactive. For example, the FEVE polymerization process leads by design to a polymer with neutral and/or anionic end groups. FEVE resins do contain a small amount of hydroxyl and carboxyl functional groups. These functional groups are classified as low concern RFG by the USEPA (1997) and OECD (2009). There are no RFG structural similarities across the polymers in this study.

Low MW leachables ($MW < 1000$ Da): All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the low MW leachable PLC criteria, which has been widely discussed (see Supporting Information: Chapter 3 for references). Many of the study polymers report no active leachables, whereas the rest cite values less than 1 ppm (Tables 4 and 5). For FEVE, it is reported that some nonfluorinated polymer PA may well remain in the uncured polymer resin. The methods and references for low MW leachables are presented in the Supporting Information: Chapter 4 with the specific chapter noted in Tables 4 and 5. The data presented in Tables 4 and 5 were determined for each of the respective polymers in this study using techniques such SEC and GPC as the predominant analytical methods along with the use of USP Class VI testing. Additional methods included 21 CFR 177.2600 (USCFR, 2022) and the USEPA's toxicity characteristic leaching procedure (TCLP; SW-846 Test Method 1311; USEPA, 1992).

Residual monomers and ratio of residual monomers to typical MW: PLC criteria of equal interest to the low MW leachables are the residual monomers and the ratio of residual monomers to typical MW (see Supporting Information: Chapter 3 for references). All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the residual monomers and ratio of residual monomers to typical MW PLC criteria. The study data presented in Tables 4 and 5 show the polymers in this study have residual monomers ranging from less than 50 ppb for several fluoropolymers and up to less than 0.1% for PCTFE based on the methods utilized. Fluoroelastomers in this study have residual monomers ranging from less than 50 ppb up to less than 5 ppm. Residual monomers were determined in several ways including dynamic and static headspace gas chromatography/mass spectrometry (GC/MS) at 150 °C. The monomers used in most cases have very low boiling points and are thus readily volatilized (and captured or destroyed) during polymer manufacture processing and drying steps. The methods and references for residual monomer determination are presented in the Supporting Information: Chapter 4 with the specific chapter noted in Tables 4 and 5. Given the very low residual monomer levels reported, the ratio of residual monomers to polymer MW range from 10^{-11} to 10^{-13} for the study polymers.

Water solubility and octanol/water partition coefficient (K_{ow}): The fluoroplastics, specialty fluoroplastics, and fluoroelastomers in this study are solids that are hydro- and oleophobic, practically insoluble in both water and n-octanol. Therefore, a K_{ow} cannot be computed and is not applicable to these substances. It is worth noting that the practical lack of solubility in water (<10 mg/L) and n-octanol indicate the inability for the study fluoropolymers to actively or passively cross cell membranes. This does mean there is no indication that these polymers can bioaccumulate or bioconcentrate in biota (Henry et al., 2018 and this study). The methods and references for solubility are presented in the Supporting Information: Chapter 4 with the specific chapter noted in Tables 4 and 5.

Particle size: To meet the PLC assessment criteria for particle size, a powder must be 5 μm or greater in size (median mass aerodynamic diameter [MMAD]). All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the particle size PLC criterion. As shown in Tables 4 and 5, the fluoroelastomers in this study are provided in sheets, blocks, pellets, or "crumb," and the fluoroplastics and specialty fluoropolymers in this study are provided in the form of powders, pellets, sheets, flake, or in dispersions. References and additional information regarding the form of the study polymers is provided in the Supporting Information: Chapter 4.

Stability: All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the PLC criteria for hydrolysis, light stability, oxidative stability, and aerobic and anaerobic biodegradability (e.g., breakdown into species with Mn <1000 Da). Public literature has abundant thermal, chemical, and biological stability data for the polymers in this study as stability is a hallmark property for these polymers (Ebnesajjad, 2017). For biodegradation, the assessments were largely made based on property data of the study polymers demonstrating they are insoluble and stable in environmental media and thus are not expected to be bioavailable and therefore not biodegrade.

Additionally, published literature reports (Drobny, 2016; Ebnesajjad, 2017; Grot, 2013; Henry et al., 2018; Polymer Industry Association [PIA], 2019) that the study polymers are stable at foreseeable maximum continuous use temperatures presented in Tables 4 and 5. All polymers, including fluoropolymers can degrade when misused or when heated above their recommended use temperatures (Fluoropolymer Products Group of Plastics Europe [FPG], 2012; PIA, 2019). Of course, users are expected to follow guidance for use provided by manufacturers. Hence, the recommended temperatures for reasonably foreseeable use for the study substances are presented in Tables 4 and 5. References and additional information regarding the stability of the study polymers is provided in the Supporting Information: Chapter 4.

Fluorinated PA: If a fluorinated PA was used in the manufacture of the polymer, it was reported for each fluoropolymer in this study. Nine of the 14 fluoropolymers in the study were reported *not* to have used a fluorinated PA in their manufacture. It is industry practice to use fluorinated PAs when it is necessary to obtain specific end-use property or performance requirements generally related to very high-polymer MWs (see also Supporting Information: Chapter 7). For five study polymers, THV, FKM, FFKM, fluorinated ionomers, and amorphous fluoropolymers, a response of "Yes and No" was provided indicating that for some polymer grades a fluorinated PA is used, but not for others. See Supporting Information: Chapter 4 for additional information.

Results summary: This study examined three fluoroelastomers, nine fluoroplastics, and two specialty fluoroplastics:

ionomers and amorphous. Data for each were gathered from the author companies and assessed by the PLC criteria applicable to the polymer itself "in use" (BIO by Deloitte, 2015; Henry et al., 2018; OECD, 2009). All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the PLC criteria based on the data presented in Tables 4 and 5 with additional details provided describing methods and references in the Supporting Information: Chapter 4.

Including the four fluoroplastics in the prior study (Henry et al., 2018), data for 18 fluoropolymers have been provided for PLC assessment. These polymers have a wide range of compositions and structures and represent most of the global commercial fluoropolymer market (see additional text in the Discussion). These 18 fluoropolymers represent the major fluoropolymers manufactured and are used worldwide in innumerable critical end-use products and applications. Tables 1 and 2 highlight examples of the end-use markets as well as critical functionality and benefits these polymers provide.

Each of the assessed polymers in this study are insoluble in both water and n-octanol, and thus K_{ow} is not applicable. This lack of solubility in water and octanol confirms that fluoropolymers are not mobile in the environment and are not bioaccumulative and not able to bioconcentrate. The stability studies reported here on each of the study fluoropolymers reveal their stability in terms of light, hydrolysis, heat, oxidation, and biodegradation. When coupled with the lack of solubility, these fluoropolymers are most often characterized as relatively inert materials in the environment. Like any other chemical material or product, it is important to follow the fluoropolymer manufacturer's recommended use and temperature conditions. Tables 4 and 5 describe these recommendations for each fluoropolymer. As reported, the physical forms of the fluoropolymers are largely pellets, blocks, crumb, sheets, some powders (all with MMAD >5 μm). The solid fluoropolymers are not nanoparticles, and concerns related to nanoparticles do not apply during normal product use. Due to the properties described above for the assessed fluoropolymers—large molecules with no water solubility—the fluoropolymers are biologically inert without the practical ability to cross cell membranes.

During the evaluation of the study fluoropolymers, there was a conscious focus on several core PLC parameters: MW, low MW leachables, % oligomers, and residual monomers, which are direct outcomes related to fluoropolymer manufacturing. In addition to what is reported here in Tables 4 and 5 for the fluoropolymers themselves, industry efforts to manage emissions during manufacturing are discussed below.

DISCUSSION

Fluoropolymers have substantial, unique societal value: Fluoropolymers possess a remarkable combination of properties and functional characteristics, as shown in Tables 1 and 2, that make them valued materials of choice in a broad range of industries and applications critical to life and a sustainable environment in the 21st century. Their unparalleled combination of properties and performance characteristics deliver functionality to a wide variety of products and systems critical to achieving important societal goals (Amcham, 2020c; FPG, 2021a; Wood, 2020b). They are strategically important to innovation in vital sectors of the global economy requiring high-speed, high-volume data transmission, miniaturization, or operations in extreme temperatures. Moreover, they are crucial to achieving important societal goals such as decarbonization, renewable energies, and/or competitiveness in the digital transition (FPG, 2021a). Fluoropolymers are indispensable for critical applications in the chemical, electronic, semiconductor, healthcare, and transport sectors and the deployment of 5G networks (FPG, 2021a). For many critical applications, fluoropolymers are the material of choice because alternatives are unable to provide the full complement of performance and functionality required. As such, there are currently no viable commercial alternatives to fluoropolymers in virtually every critical application in which they are used (FPG, 2021a, 2017; PFP, 2020).

Commercial fluoropolymers in this study meet the PLC criteria: Widely used by regulators, PLC criteria have been established around the world and documented by OECD expert groups as an appropriate hazard assessment methodology for polymers in-use and can effectively identify low risk fluoropolymers to help prioritize regulatory action (BIO by Deloitte, 2015; OECD, 1993, 2009). Here, we present PLC data, for hazard assessment, that define a group of fluoropolymers' "in-use" properties. PLC is not a comprehensive life-cycle assessment tool. Full life-cycle assessments consider all phases of product "life" including creation (manufacturing) and end-of-life (disposal). Information on manufacture and end-of-life is provided later in this study. Recently, polymers have been under increased regulatory scrutiny. In 2019, the industry-led European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC) developed a Conceptual Framework for Polymer Risk Assessment ("CF4Polymers"; ECETOC, 2019). CF4Polymers provides guiding elements to be considered in assessing potential ecological and human health hazards and risks posed by polymer substances. CF4Polymers also considers specific life-cycle stages of polymer products and their associated routes of exposure. The authors of the CF4Polymers framework support the PLC approach as a means to accomplish polymer risk assessment. They specifically support the findings of Henry et al. (2018) and state that they are "unaware of scientific evidence to justify generally assigning fluoropolymers the same level of regulatory concern as other PFAS" (ECETOC, 2019). In 2020, the European Commission contracted a study to propose criteria to identify PRR under REACH (Wood, 2020a). The report states that the authors consider fluoropolymers meeting the criteria to be considered PLC, "following the recommendations of Henry et al. (2018)."

The properties and characteristics of fluoropolymers are anchored in the strength of the carbon–fluorine bond, which render them highly stable (thermally, chemically, and biologically), inert, and durable—long lasting in use—under exacting and high-performance conditions. Physical, chemical, thermal, and biological stability are important criteria for a polymer to be considered a PLC. The data presented in Tables 4 and 5 demonstrate that commercial fluoropolymers from the author companies meet the criteria to be considered PLC. The PLC criteria for physicochemical properties reflect the state of the polymers in this study, solids, as well as their inertness and stability. None of the fluoropolymers assessed in this study were soluble in water or octanol. They are biologically inert, insoluble in water and octanol, and not expected to move in or between environmental media. Fluoropolymers are also twice as dense as water. These properties and water insolubility mean fluoropolymers are not mobile in the environment and therefore would not be expected to be found in sources of drinking water. Fluoropolymers are neither bioavailable nor bioaccumulative. These solid polymers cannot be absorbed through a cell membrane via passive or active transport and do not bind or interact with the cell surface (see also Supporting Information: Chapter 8). In addition, whereas aquatic and mammalian toxicology studies of fluoropolymers may be desirable for some, they are technically difficult for insoluble, solid, high-MW polymers. The OECD test guidelines reiterate this in many cases. This is confirmed for example in REACH Annex VII guidance, which repeatedly states toxicity is unlikely to occur "if a substance is highly insoluble in water or the substance is unlikely to cross biological membranes" (see Supporting Information: Chapter 9).

Finally, structure criteria including MW, MWD, residual monomer(s), oligomers, and other synthesis by-products, as represented by low MW extractables and leachables have been determined for the fluoropolymers presented and meet values established for the PLC criteria and regulated uses (e.g., USP). The concentrations in the fluoropolymer that have been evaluated are extremely low, reflective of effective manufacturing processes that minimize these compounds complemented by capture and/or destruction systems for such materials. For additional information, see the section below discussing responsible manufacturing. This study and prior work (Henry et al., 2018) provide a guide for other global fluoropolymer manufacturers to gather and present data on additional commercial fluoropolymers to determine if they too meet the PLC criteria.

Fluoropolymer stability, aka persistence, is not an intrinsic hazard: Fluoropolymers are stable, inert, solid materials. Fluoropolymers resist degradation by acids, bases, oxidants, reductants, photolytic processes, microbes, and metabolic processes; for this reason, they are thermally, chemically, and biologically highly inert. Fluoropolymer stability was presented in the introduction and is further considered in the Supporting Information: Chapters 4 and 5. Fluoropolymers are not expected to degrade under environmental conditions or normal use and processing conditions (Wood, 2020a). They are stable and remarkably durable and are therefore persistent. However, persistence alone does not imply that there is a present or future risk to human health or the environment (Rüdel et al., 2020). Persistence itself is not an intrinsic hazard, as it does not in itself imply or inform the potential for an adverse effect (aka toxicity). There is no language in REACH supporting the notion that persistence alone justifies risk-management measures. REACH has regulated persistence in combination with other properties that do inform potential hazards. In fact, REACH combines persistence with bioaccumulation and toxicity (or "very persistent" with "very bioaccumulative/very mobile" vPvB/vPvM) to justify designation as a substance of very high concern (SVHC) and consideration of potential risk-management measures for uses associated with unacceptable risk. Therefore, persistence on its own does not justify the need for specific risk-management measures. Fluoropolymers themselves are persistent, but they are not bioaccumulative, not mobile, and not toxic and therefore not SVHCs from a regulatory perspective (Ruwona and Henry, 2021).

PFAS grouping and segmentation—Scope of regulatory measures: The OECD definition of PFAS is based only on chemical structure (OECD, 2021). It describes a universe of fluorinated organic substances with vastly different physical, chemical, and biological properties, including polymers and nonpolymers; solids, liquids, and gases; highly reactive and inert substances; soluble and insoluble substances; and volatile and involatile substances and is too broad to allow effective, science-based assessment and regulation of chemical compounds as an entire group (Amcham 2020a; BDI, 2021; Buck et al., 2021; Orgalim, 2021; Wallington et al., 2021). A 2021 OECD report states: "it is highly recommended that such diversity be properly recognized and communicated in a clear, specific and descriptive manner" and "the term 'PFASs' does not inform whether a compound is harmful or not, but only communicates that the compounds under this term share the same trait for having a fully fluorinated methyl or methylene aliphatic carbon moiety" (OECD, 2021).

In this context, the available property data (Tables 4 and 5) reveal that fluoropolymers have distinctly different properties from nonpolymeric PFAS and from SCFPs that have a polymeric backbone that does not contain C–F bonds directly attached to it. The perfluoroalkyl moiety in SCFPs is found in a side-chain connected via a functional group to the polymer backbone and "can potentially lead to the formation of nonpolymer PFAS as a result of degradation" (Fluoropolymer Products Group of Plastics Europe [FPG], 2021b; Wood, 2020a; see Supporting Information: Chapter 6). Segmentation that clearly differentiates the broad PFAS family according to their properties, rather than using a structure-based classification alone (OECD, 2021), is needed for a scientifically sound, risk-based regulatory approach. Regulating all PFAS as one homogenous group (ECHA, 2020) absent consideration of their properties, particularly when the properties are so demonstrably different, neglects basic scientific consideration of these properties, which are the foundation of substance differentiation. The USEPA does not consider all PFAS to have similar risk profiles and therefore they are following a categorical grouping approach based on information about similarities in structure, physicochemical properties, and existing test data on the toxicity of PFAS (USEPA, 2021b). Therefore, segmentation based on properties should be conducted before performing any grouping-based risk assessment, placing stable, nonhazardous fluoropolymers that meet the criteria to be considered PLC in a separate category (see also Supporting Information: Chapter 6).

Fluoropolymer market perspective: The commercial fluoropolymer global market sales have been reported to be approximately 230 000 MT (Dams & Hintzer, 2017). Given the expected fluoropolymer market growth, ranging from approximately 4%–5% to 7%–8% (Allied Market Research [AMR], 2022; Future Market Insights [FMI], 2022; FPG, 2021a; Globe Newswire, 2021), a pro forma market table was created for 2021 using a 5% growth rate. Adding ionomers as well as updated amorphous market information (company data) to the above, the total commercial fluoropolymer market sales is estimated to be approximately 330 000 MT in 2021 (see Supporting Information: Chapter 10). Four fluoropolymers: PTFE, FEP, PFA, and ETFE, were the focus of the first fluoropolymer PLC paper (Henry et al., 2018) and account for approximately 64% of fluoropolymers sold globally in 2021 (pro forma basis). The sales volume of these four fluoropolymers is represented by the first four bars in Figure 10.1 in Supporting Information: Chapter 10. This study discusses 14 fluoropolymers representing an additional 32% (pro forma basis) of the global fluoropolymer market. Therefore, this study, in combination with Henry et al. (2018), presents PLC data from the cited manufacturers of commercial fluoropolymers representing approximately 96% of the global commercial fluoropolymer market that meet the criteria to be considered PLC. The projected 2021 sales volume of the major types of commercial fluoropolymers covered in this study (PVDF, FKM, FEPM, amorphous, ionomers, THV, ECTFE, PCTFE, and FFKM, EFEP, CTP, and FEVE) are also represented in Figure 10.1 in Supporting Information: Chapter 10. As noted, estimated market volumes were provided for the sum of FEPM, CPT, EFEP, and FEVE as well as a small "others" category. The fluoropolymer polyvinyl fluoride (PVF) was not covered by these two papers but is also shown in Figure 10.1 in Supporting Information: Chapter 10. Other fluorinated polymers, perfluoropolyethers, and SCFPs are not addressed in this study (see Supporting Information: Chapter 6).

FLUOROPOLYMER LIFE-CYCLE CONSIDERATIONS

This study focuses on the properties of the 14 selected commercial fluoropolymers themselves in-use providing data that demonstrate they meet the criteria to be considered PLC. Additionally, the life-cycle stages of fluoropolymer creation (manufacturing) and disposal at the end of industrial or consumer use (end-of-life) are important to consider. The primary focus in these life-cycle stages is generally nonpolymer PFAS from the manufacturing process or fluoropolymer degradation in end-of-life disposal (ECHA, 2020; FPG, 2021a; Guelfo et al., 2021; Lohmann et al., 2020).

The long-established life-cycle assessment approach to environmental protection and risk management first considers the extent of emissions, their toxicity, and their exposure potential (Guinee et al., 2011). When emissions are sufficiently large in scope, toxicity, and exposure potential, emission-management methods are then considered, including process input changes and emission controls to reduce or eliminate the risk of the emissions. Fluoropolymer manufacturing and disposal life-cycle stages were discussed in the paper that first presented fluoropolymer PLC data (Henry et al., 2018). Here we provide an update and current perspective.

Responsible manufacturing: As corroborated by the data presented here and in prior work (Henry et al., 2018), a large volume percentage and number of commercial fluoropolymers are manufactured that meet the criteria to be considered PLC. Emissions from fluoropolymer manufacture are a key product life-cycle focus. The main focus during the manufacturing phase is not directly related to fluoropolymers but from emissions. Emissions of concern may include nonpolymer PFAS such as fluorinated PAs, unreacted monomers, oligomers, or other unintended by-products formed during manufacturing. It is important to note that, although some high-MW fluoropolymers require use of a fluorinated PA in manufacturing (see also Supporting Information: Chapter 10), it has been reported that at least 50% of commercial fluoropolymers are made without one (Pro-K Fluoropolymer Group, 2021).

Recently, a group of fluoropolymer member companies of FPG voluntarily committed to responsible manufacturing principles through the commissioning of a Regulatory Management Option Analysis, developed by independent consulting firm Chemservices (FPG, 2021a). Member companies of this group are working on individual projects and joint projects at the trade association level with third-party experts. Specifically, companies have committed to continuously improving and/or developing the best available techniques in the manufacturing process, managing environmental emissions, developing R&D programs for the advancement of technologies allowing for the replacement of nonpolymer PFAS PAs and/or working with downstream users to increase the recyclability and reuse of its products in line with the objectives of circular economy (FPG, 2021a). Implementation of this voluntary industry initiative to address concerns relating to fluoropolymers will strengthen already ongoing efforts performed by the fluoropolymer industry promoting responsible manufacturing practices. In addition, member companies are committed to working with EU authorities to establish and implement technical actions to guarantee adequate control of the risks derived from the manufacture and use of fluoropolymers to mitigate such risks wherever possible. This will be done following transparency principles and agreements to monitor progress. For example, important emission reduction has been demonstrated by major fluoropolymer manufacturers including fluorinated PA recovery for reuse, 99% removal of fluorinated PA in wastewater treatment, and

99.99% capture and destruction efficiency of gaseous emissions routed to a thermal oxidizer (Chemours, 2021c), as well as 99–99.9 plant emission reductions (Daikin, 2021c, 2022). Four other companies have reported replacement of fluorinated PAs with nonfluorinated PAs (Arkema, 2008, 2021b; Chemours, 2022; Gujarat Fluorochemicals Limited, 2022; Solvay, 2022). These are substantial efforts toward mitigating emissions associated with fluoropolymer manufacturing being worked on by fluoropolymer manufacturers. This study and the prior study (Henry et al., 2018) provide a guide for other global fluoropolymer manufacturers to gather and present data on their commercial fluoropolymers in-use demonstrating that they meet the PLC criteria.

End-of-use: At the end of industrial or consumer use, fluoropolymers may be disposed via the following routes: landfill, incineration (e.g., waste-to-energy [WTE] facilities), or reuse/recycling. There is considerable data demonstrating that fluoropolymers such as PTFE do not degrade in the environment or release substances of toxicological or environmental concern (FPG, 2021a; Hintzer & Schwertfeger, 2014). FPG member companies are working with the industry and end users on this subject and are engaged in a research project aimed at identifying conditions required for proper disposal (incineration) of fluoropolymers (FPG, 2021a).

Fluoropolymers are chemically, thermally, and biologically stable (Henry et al., 2018; this study) and therefore are not expected to transform to dispersive nonpolymeric PFAS when disposed of in a landfill. A recent study presented results from OECD guideline biodegradation studies demonstrating that PTFE is stable and does not degrade under environmentally relevant conditions (Ruwona and Henry, 2021). Further, fluoropolymers that meet the criteria to be considered PLC, such as those in this study and prior work (Henry et al., 2018), have negligible leachables, unreacted monomers, and oligomers most likely destroyed in fluoropolymer use processing and would therefore not be expected to significantly contribute to landfill leachate (Ruwona and Henry, 2021).

Available data reveal that fluoropolymers are mineralized (i.e., all C–F bonds broken, hydrofluoric acid generated, and scrubbed to calcium fluoride) under commercial WTE incineration operating conditions (Aleksandrov et al., 2019; Bakker et al., 2021; DEC, 2021; Giraud et al., 2021a, 2021b). In recent pilot scale studies representative of full-scale WTE facilities, the most common form of end-of-life destruction conducted on PTFE found that combustion converted the fluorine into controllable hydrogen fluoride gas and that, of the 31 PFAS studied, no fluorine-containing products of incomplete combustion were produced above background levels (Aleksandrov et al., 2019). Further, a recent study investigating the presence of PFAS in waste incinerator flue gas stated: "based on a literature review, RIVM expects that most of the PFASs will largely degrade during the incineration process and then be removed when the flue gases are cleaned. The remaining PFASs are expected to be removed during the recovery of the carbon dioxide" (Bakker et al., 2021). The RIVM report affirmed that PTFE is the most stable fluorine-containing polymer. For PTFE, the RIVM report concluded that complete thermal decomposition is achieved at a temperature of approximately 800 °C. It was therefore assumed that other fluorine-containing polymers also thermally decompose completely at a temperature of 800 °C. Temperatures at the pyrolysis front and the combustion front in the waste-burning bed range from 900 °C to 1100 °C (Asthana et al., 2006; Ménard et al., 2006), which is well above 800 °C, the temperature at which the complete thermal decomposition of PTFE is achieved (Bakker et al., 2021). Studies for additional fluoropolymers and those with additional pilot and/or full-scale fluoropolymer studies would contribute to this body of data and further affirm their results. The PFP and FPG currently have joint projects working on these potential contributions.

Recycling of fluoropolymer products and articles containing fluoropolymers is difficult because separation of the fluoropolymer from the end products is not always possible (FPG, 2021a; Hintzer & Schwertfeger, 2014; Pro-K Fluoropolymer Group, 2018). This is because fluoropolymers are used predominantly in small components of larger finished articles involving a wide variety of materials. There are several options to recycle fluoropolymer products. In primary recycling, solid fluoropolymer waste is ground and later fed back into the manufacturing cycle of some fluoropolymer products. Recycled fluoropolymers may be used in high-end applications when correctly collected, cleaned, and reprocessed. In secondary recycling, solid fluoropolymer waste is ground, followed by degradation to approximately 1% of the original degree of polymerization by using electron beams, gamma rays, or thermomechanical degradation. The recovered material can be used in the manufacturing of new fluoropolymer products. Lastly, in tertiary recycling or upcycling, solid fluoropolymer is ground, then decomposed into the starting monomers at temperatures higher than 600 °C (pyrolysis) to obtain the same chemical components from which the fluoropolymer was manufactured; monomers, such as tetrafluoroethylene, are purified by distillation, and can then be reused to manufacture new fluoropolymer (3M, 2021; Schlipf & Schwalm, 2014). For the primary and secondary schemes, recycling treatments can be undertaken by the manufacturers of fluoropolymers themselves (onsite), or at a larger scale, mainly by specialist recycling companies. The upcycling needs to be colocated to a fluoropolymer manufacturing plant that can use tetrafluoroethylene.

Primary and secondary recycling is limited because of the presence of fillers, colorants, and other materials in the composition of their final articles. Further, recycling might not work for all end-of-life components, as they are used predominantly in small components of larger finished articles involving a wide variety of materials. Therefore, collecting and dismantling for recycling might not be feasible for all products (FPG, 2021a; Hintzer & Schwertfeger, 2014; Pro-K Fluoropolymer Group, 2018). However, it should be noted that upcycling treatment is applicable to some articles containing fluoropolymers, such as pipe liners in chemical plants, as well as other plant components such as pumps, tank liners, seals, hoses, compensators, and many other fluoropolymer components and systems. These are the products for which the high quantities of fluoropolymers are used offering significant recycling potential.

SUMMARY

This study has described the composition, uses, performance properties, and functionalities of 14 commercially available fluoropolymers, including fluoroplastics and fluoroelastomers. Fluoropolymers are the preferred material of choice because of their unique combination of properties, which are not achievable from other materials or via other functions. As a result, fluoropolymers have become a critical mainstay for society and are useful to modern living, as they provide vital, reliable functionality to a broad range of industrial and consumer products. Further, the study has presented data demonstrating the subject fluoropolymers satisfy the widely accepted polymer hazard assessment criteria to be considered PLC. The data presented demonstrate the fluoropolymers in the study are thermally, biologically, and chemically stable, negligibly soluble in water, nonmobile, nonbioavailable, nonbioaccumulative, and nontoxic, and contain low levels of impurities. These results further demonstrate that the fluoropolymer class should be considered distinctly different and should not be grouped with other PFAS for hazard assessment or regulatory purposes. When combined with earlier work (Henry et al., 2018), the study demonstrates that commercial fluoropolymers are available that meet the criteria to be considered PLC, which represent approximately 96% of the global fluoropolymer market. Lastly, emissions from fluoropolymer manufacture and disposal at end-of-use are a product life-cycle focus. Emissions may include nonpolymer PFAS such as fluorinated PAs, unreacted monomers, oligomers, or other unintended byproducts formed during manufacturing. Fluoropolymer manufacturers recently committed voluntarily to responsible manufacturing principles by continuously improving and/or developing the best available techniques in the manufacturing process, managing environmental emissions, developing R&D programs for the advancement of technologies allowing for the replacement of fluorinated PAs, and/or increasing recyclability and reusing fluoropolymers in line with the objectives of circular economy.

ACKNOWLEDGMENT

The authors thank GSI Environmental for assisting with this study as well as the many colleagues, including Thomas Labour, Florence Churlaud, Catherine Savary, and Betsy Edhlund who provided valuable knowledge to accomplish the study, and all the reviewers for providing valuable comments on this manuscript. There are no funders to report for this submission.

CONFLICT OF INTEREST

The authors are employed by companies that commercially manufacture fluoropolymers. SHK is an independent fluorotechnology consultant working on behalf of AGC Chemicals Americas Inc. and principal of BeachEdge Consulting LLC.

DATA AVAILABILITY STATEMENT

Data gathered for this paper is presented in the paper itself and the Supporting Information: Data file provided. Additional data are available upon request from the corresponding author Stephen Korzeniowski (shkorzo@gmail.com).

SUPPORTING INFORMATION

The Supplement contains a glossary of terms as well as additional information on the study of fluoropolymers properties and functionalities, polymer of low concern (PLC) background and criteria, references and methods for the PLC data for the study of fluoropolymers, benefits, features and alternatives assessment for the study of fluoropolymers, the differences between fluoropolymers and side-chain fluorinated polymers, fluoropolymer bioavailability and toxicity studies, fluoropolymer global market information, fluoropolymer socioeconomic analyses and risk-management options analysis (RMOA).

ORCID

Robert C. Buck http://orcid.org/0000-0002-2604-8905

REFERENCES

3M. (2021). *Up-cycling. Closing the loop*. https://multimedia.3m.com/mws/media/907323O/up-cycling-fluoropolymers-brochure.pdf?fn=Up-Cycling_Brochure_EN.pdf

AGC Chemicals Company. (2021a). *FEVE LUMIFLONbrochure®*. https://www.agcchem.com/wp-admin/admin-ajax.php?juwpfisadmin=false&action=wpfd&task=file.download&wpfd_category_id=170&wpfd_file_id=1927&preview=1&embedded=true

AGC Chemicals Company. (2021b). *Cytop® amorphous fluoropolymers*. https://www.agc-chemicals.com/jp/en/fluorine/products/detail/index.html?pCode=JP-EN-F019

AGC Chemicals Company. (2021c). *Forblue™ Flemion™ fluorinated ion-exchange membranes*. https://www.agc-chemicals.com/jp/en/fluorine/products/category/result.html?c_id=11

AGC Chemicals Company. (2021d). *AFLAS fluoroelastomers*. https://www.agcchem.com/wp-admin/admin-ajax.php?juwpfisadmin=false&action=wpfd&task=file.download&wpfd_category_id=172&wpfd_file_id=1901&preview=1&embedded=true

Aleksandrov, K., Gehrmann, H. J., Hauser, M., Matzing, H., Pigeon, D., Stapf, D., & Wexler, M. (2019). Waste incineration of polytetrafluoroethylene (PTFE) to evaluate potential formation of per- and poly-fluorinated alkyl substances (PFAS) in flue gas. *Chemosphere*, *226*, 898–906. https://doi.org/10.1016/j.chemosphere.2019.03.191

Allied Market Research (AMR). (2022). *Fluoropolymers market by product type*. https://www.alliedmarketresearch.com/fluoropolymers-market

American Chamber of Commerce in Europe (Amcham). (2020a). *Grouping of PFAS: Regulation by distinct PFAS classes is scientifically superior to classification by a broad PFAS group*. https://www.amchameu.eu/position-papers/grouping-pfas-regulation-distinct-pfas-classes-scientifically-superior

American Chamber of Commerce in Europe (Amcham). (2020b). *A narrow regulatory focus on persistence-only is not justifiable and can undermine innovation to produce materials that support societal sustainability goals*. https://www.amchameu.eu/position-papers/use-persistency-and-mobility-criteria-chemicals-regulation-amcham-eu-comments

American Chamber of Commerce in Europe (Amcham). (2020c). *REACH Restriction: Essential use criteria in the context of socio-economic impact analysis when unacceptable risk is demonstrated*. https://www.amchameu.eu/position-papers/reach-restriction-essential-use-criteria-context-socio-economic-impact-analysis-when

Ameduri, B. (2020). The promising future of fluoropolymers. *Macromolecular Chemistry and Physics*, *221*, 1900573. https://doi.org/10.1002/macp.201900573

Améduri, B., Boutevin, B., & Kostov, G. (2001). Fluoroelastomers: Synthesis, properties and applications. *Progress in Polymer Science (Oxford)*, *26*(1), 105–187. https://doi.org/10.1016/S0079-6700(00)00044-7

Ameduri, B., & Sawada, H. (2017a). *Fluorinated polymers. Volume 1: Synthesis, properties, processing and simulation*. Royal Society of Chemistry.

Ameduri, B., & Sawada, H. (2017b). *Fluorinated polymers. Volume 2: Applications*. Royal Society of Chemistry. https://doi.org/10.1039/9781782629368

Arkema. (2008). *Arkema eliminates fluorosurfactants from Kynar 500PVDF®*. https://www.pcimag.com/articles/88876-arkema-eliminates-fluorosurfactants-from-kynar-500-pvdf

Arkema. (2021a). *KynarPVDF family®*. https://www.extremematerials-arkema.com/en/product-families/kynar-pvdf-family/chemical-resistance-fuel-resista/download-kynar-pvdf-chemical-res/

Arkema. (2021b). *Fluorosurfactant free KynarPVDF resin®*. https://kynar500.arkema.com/en/product-information/fluorosurfactant-free/

Asahi-Kasei. (2021). *Aciplexion exchange membranes®*. https://www.asahi-kasei.co.jp/salt-electrolysis/en/?_ga=2.192307178.1574253781.1637252713-425530764.1637252713

Asthana, A., Ménard, Y., & Patisson, F. (2006). A 2-D mathematical model of on-grate municipal solid waste combustion. In F. Kongoli & R. G. Reddy (Eds.), *Sohn International Symposium Advanced Processing of Metals and Materials, Volume I—Thermo and physicochemical principles: non-ferrous high-temperature processing* (pp. 465–474). The Minerals, Metals & Materials Society (TMS).

ASTM. (2021). *Standard practice for rubber and rubber latices—Nomenclature* (pp. D1418–D1421). ASTM International. https://doi.org/10.1520/D1418-21

Atkinson, S. (2018). Essential high-purity sealing materials for semiconductor manufacturing. *Sealing Technology*, *7*, 5–7. https://doi.org/10.1016/S1350-4789(18)30284-8

Auer, C. M., Nabholz, J. V., & Baetcke, K. P. (1990). Mode of action and the assessment of chemical hazards in the presence of limited data: Use of structure-activity relationships (SAR) under TSCA, Section 5. *Environ Health Perspect*, *87*, 183–197.

Bakker, J., Bokkers, B., & Broekman, M. (2021). *Per- and polyfluorinated substances in waste incinerator flue gases* (RIVM Report 2021-0143). https://www.rivm.nl/bibliotheek/rapporten/2021-0143.pdf

Banks, R. E., Smart, B. E., & Tatlow, J. C. (1994). *Organofluorine chemistry: Principles and commercial applications*. Plenum.

Barnwell. (2021). *Perfluoroelastomer O rings (FFKM)*. https://www.barnwell.co.uk/products/perfluoroelastomer-ffkm-o-rings/

Beyer, E. C. (1993). Gap junctions. *International Review of Cytology*, *137*, 2.

BIO by Deloitte. (2015). *Technical assistance related to the review of REACH with regard to the registration requirements on polymers* (Final Report). Prepared for the European Commission (DG ENV) in collaboration with PIEP.

Buck, R. C., Franklin, J., Berger, U., Conder, J. M., Cousins, I. T., de Voogt, P., Jensen, A. A., Kannan, K., Mabury, S. A., & van Leeuwen, S. P. J. (2011). Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins. *Integrated Environmental Assessment and Management*, *7*(4), 513–541. https://doi.org/10.1002/ieam.258

Buck, R. C., Korzeniowski, S. H., Laganis, E., & Adamsky, F. (2021). Identification and classification of commercially relevant per- and polyfluoroalkyl substances (PFAS). *Integrated Environmental Assessment and Management*, *17*(5), 1045–1055. https://doi.org/10.1002/ieam.4450

Bundesverband der Deutschen Industrie e.V. (BDI). (2021). *EU chemicals Legislation: Restriction of PFAS (EN)*. english.bdi.eu/publication/news/eu-chemicals-strategy-restriction-of-pfas/

Chemours. (2021a). *Nafion™ ion exchange materials*. https://www.nafion.com/en

Chemours. (2021b). *Economic and environmental improvements with versatile membranes*. https://www.nafion.com/en/support/white-papers/versatility-of-ion-exchange-membranes-white-paper

Chemours. (2021c). *Thermal oxidizer destroying PFAS at greater than 99.99% efficiency*. https://www.chemours.com/en/-/media/files/corporate/fayetteville-works/2020-0320-thermal-oxidizer-efficiency-results-announced.pdf?rev=87dbfd0ebb9c45aeaa475fddd2a899b4&hash=05916EC2AC2B5A3C41135773A3FCDED0

Chemours. (2022). *Chemours announces process innovation with New Viton™ fluoroelastomers advanced polymer architecture (APA) offering*. https://www.chemours.com/en/news-media-center/all-news/press-releases/2022/chemours-announces-process-innovation-with-new-viton-fluoroelastomers-advanced-polymer-architecture

Curbell. (2021). *PCTFE*. https://www.curbellplastics.com/Research-Solutions/Materials/PCTFE

Daemar. (2021). *DuPont Kalrez—Oil and gas product selector guide®*. https://daemar.com/wp-content/uploads/2017/11/OilGasProduct-SelectorGuide_KZE-A40042-00-A0217.pdf

Daikin. (2011a). *EFEP. Fluoropolymer handbook* (pp. 84–93). Daikin Industries.

Daikin. (2011b). *CPT. Fluoropolymer handbook* (pp. 58–62). Daikin Industries.

Daikin. (2021a). *NeoflonPCTFE®*. https://www.daikinchemicals.com/solutions/products/fluoropolymers/neoflon-pctfe.html?_ga=2.84898265.1754525417.1636603879-520575968.1622167042

Daikin. (2021b). *Neoflon CPT*. https://www.daikinchemicals.com/solutions/products/fluoropolymers/neoflon-cpt.html?_ga=2.257391307.1754525417.1636603879-520575968.1622167042

Daikin. (2021c). *Daikin–A responsible steward for PFAS emission reductions and safe alternatives*. https://www.daikinchem.de/sites/default/files/pdf/News/Daikin_Responsible_Steward_PFAS_Emission_Reduction_210601.pdf

Daikin. (2022). *Measures concerning environment emission of PFAS*. https://www.daikinchemicals.com/company/sustainability/pfas.html?_ga=2.233775006.1492271271.1653437409-1591380784.1653437409

Dams, R., & Hintzer, K. (2017). Chapter 1: Industrial aspects of fluorinated oligomers and polymers. In B. Ameduri & H. Sawada (Eds.), *Fluorinated polymers Volume 2: Applications* (pp. 3–31). Royal Society of Chemistry, Cambridge.

Darden, W., & Parker, R. (2021). *Fluoropolymer coatings for plastics*. AGC Chemicals. https://lumiflonusa.com/wp-content/uploads/FluoropolymerCoatingsForPlastics.pdf

Domininghaus, H. (1998). Chapter 2.1.7.4: Tetrafluorethylen/hexafluorpropylen/vinylidenfluorid-terpolymer. In *Kunststoffe, Eigenschaften und Anwendungen* (5th ed., 564f, pp. 525–598). Springer. https://books.google.com/books?id=Ar-oBgAAQBAJ&printsec=frontcover#v=onepage&q&f=false

Drobny, J. G. (2016). *Fluoroelastomers handbook* (2nd ed.). Elsevier. https://www.elsevier.com/books/fluoroelastomers-handbook/drobny/978-0-323-39480-2

Ebnesajjad, S. (2000). *Fluoroplastics Volume 1. Non-melt processible fluoroplastics*. PDL Handbook Series. Plastics Design Laboratory.

Ebnesajjad, S. (2003). *Fluoroplastics Volume 2. Melt processible fluoropolymers*. PDL Handbook Series. Plastics Design Laboratory.

Ebnesajjad, S. (2017). Introduction to fluoropolymers. In *Applied plastics engineering handbook: Processing, materials, and applications* (2nd ed., pp. 55–71). Elsevier. https://doi.org/10.1016/B978-0-323-39040-8.00003-1

ECETOC. (2019). *The ECETOC conceptual framework for polymer risk assessment (CF4POLYMERS)* (Technical Report No. 133-1). May. https://www.ecetoc.org/publication/tr-133-the-ecetoc-conceptual-framework-for-polymer-risk-assessment-cf4polymers/

ECHA. (2020). *The national authorities of Germany, the Netherlands, Norway, Sweden and Denmark invite interested parties to send in evidence and information on the use of per- and polyfluoroalkyl substances (PFAS)*. https://echa.europa.eu/-/five-european-states-call-for-evidence-on-broad-pfas-restriction

Environment & Infrastructure Solutions UK Limited (Wood). (2020a). *Scientific and technical support for the development of criteria to identify and group polymers for Registration/Evaluation under REACH and their impact assessment* (European Commission Report). Brussels. https://circabc.europa.eu/ui/group/a0b483a2-4c05-4058-addf2a4de71b9a98/library/4acda744-777f-473e-b084-76e125430565/details

Environment & Infrastructure Solutions UK Limited (Wood). (2020b). *Socio-economic assessment (SEA) of the US fluoropolymer industry* (Final Report 2020_0225). https://fluoropolymerpartnership.com/wp-content/uploads/2020/03/Socio-Economic-Assessment-of-the-US-Fluoropolymer-Industry-Executive-Summary.pdf

European Commission (EC). (2021). *A European green deal*. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

Fiedler, H., Kennedy, T., & Henry, B. J. (2020). A critical review of a recommended analytical and classification approach for organic fluorinated compounds with an emphasis on per- and polyfluoroalkyl substances (PFAS). *Integrated Environmental Assessment and Management*, *17*(2), 331–351. https://doi.org/10.1002/ieam.4352

Fluoropolymer Products Group of Plastics Europe (FPG). (2012). *Guide for the safe handling of fluoropolymer resins*. https://fluoropolymers.plasticseurope.org/index.php/fluoropolymers/irreplaceable-uses-1/reports-policy-documents/tfe-safe-handling-guide

Fluoropolymer Products Group of Plastics Europe (FPG). (2017). *Socio-economic analysis of the European fluoropolymer industry*. https://fluoropolymers.plasticseurope.org/application/files/7816/1167/4026/Final_SEA_Fluoropolymers_summary2017_3.pdf

Fluoropolymer Products Group of Plastics Europe (FPG). (2021a). *Risk management options analysis (RMOA)*. https://fluoropolymers.plasticseurope.org/index.php/fluoropolymers/irreplaceable-uses-1/reports-policy-documents/rmoa

Fluoropolymer Products Group of Plastics Europe (FPG). (2021b). *Fluoropolyers vs. side-chain fluorinated polymers*. https://fluoropolymers.plasticseurope.org/application/files/3516/3913/1778/Fluorpolymers_vs._side_chain_fluorinated_polymers_final.pdf

Future Market Insights (FMI). (2022). *Fluoropolymer market overview*. https://www.futuremarketinsights.com/reports/fluoropolymers-market

Gangal, S. V., & Brothers, P. D. (2010). Perfluorinated polymers, Tetrafluoroethylene-perfluorodioxole copolymers. In *Encyclopedia of polymer science and technology*. John Wiley & Sons Inc. https://doi.org/10.1002/0471440264.pst420.pub2

Giraud, R. J. (2021b). *Municipal waste-to-energy combustion of fluorinated polymers as a potential source of PFOA in the environment*. PhD thesis, University of Delaware.

Giraud, R. J., Taylor, P. H., & Huang, C.-P. (2021a). Combustion operating conditions for municipal waste-to-energy facilities in the U.S. *Waste Management*, *132*, 124–132. https://doi.org/10.1016/j.wasman.2021.07.015

Globe Newswire. (2021). *Global fluoropolymers market is forecasted to grow at a CAGR of 4.3% during the forecast period 2017–2027*. https://www.globenewswire.com/news-release/2021/08/31/2289045/28124/en/Global-Fluoropolymers-Market-is-Forecasted-to-Grow-at-a-CAGR-of-4-3-During-the-Forecast-Period-2017-2027.html

Greene-Tweed. (2021a). *FKM versus FFKM–A comparison of properties*. https://live-greene-tweed.pantheonsite.io/wp-content/uploads/2020/04/FKM-vs-FFKM-Properties-Comparison-R3.pdf

Green-Tweed. (2021b). *FKM vs. FFKM*. https://www.gtweed.com/materials/fkm-vs-ffkm/

Groh, W., & Zimmermann, A. (1991). What is the lowest refractive index of an organic polymer? *Macromolecules*, *24*(25), 6660–6663. https://doi.org/10.1021/ma00025a016

Grot, W. (2011). *Fluorinated ionomers*. PDL Handbook Series. Elsevier Inc. https://doi.org/10.1016/C2010-0-65926-8

Grot, W. (2013). Chapter 12: Fluorinated ionomers: History, properties and applications. In S. Ebenesajjad (Ed.), *Introduction to fluoropolymers* (pp. 277–291). Elsevier. https://doi.org/10.1016/B978-0-323-39040-8.00003-1

Guelfo, J. L., Korzeniowski, S., Mills, M. A., Anderson, J., Anderson, R. H., Arblaster, J. A., Conder, J. M., Cousins, I. T., Dasu, K., Henry, B. J., Lee, L. S., Liu, J., McKenzie, E. R., & Willey, J. (2021). Environmental sources, chemistry, fate and transport of per- and polyfluoroalkyl substances: State of the Science, key knowledge gaps, and recommendations presented at the August 2019 SETAC Focus Topic Meeting. *Environmental Toxicology and Chemistry*, *40*, 3234–3260. https://doi.org/10.1002/etc.5182

Guinee, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., & Rydberg, T. (2011). Life cycle assessment: past, present, and future. *Environmental Science and Technology*, *45*(1), 90–96. https://doi.org/10.1021/es101316v

Gujarat Fluorochemicals Limited. (2018). *InoflarPVDF resins*™. https://www.inoflar.com/

Gujarat Fluorochemicals Limited. (2022). *Company announcement on the development of a non-fluorinated polymerization aid*. https://gfl.co.in/upload/pages/ebce5fed9030753d0ee651bf1f48d0a0.pdf

Hafer, J. (2021). REACH registration of polymers: Identifying polymers of low concern. *ICRL*, *1*(2021), 21–25. https://chemservice-group.com/wp-content/uploads/2021/03/icrl_2021_01.pdf

Henry, B., Carlin, J., Hammerschmidt, J., Buck, R. C., Buxton, L., Fiedler, H., Seed, J., & Hernandez, O. (2018). A critical review of the application of polymers of low concern and regulatory criteria to fluoropolymers. *Integrated Environmental Assessment and Management*, *14*(3), 316–334. https://doi.org/10.1002/ieam.4035

Hintzer, K., & Schwertfeger, W. (2014). Fluoropolymers—Environmental aspects. In D. W. Smith, S. T. Iacono, & S. S. Iyer (Eds.), *Handbook of fluoropolymer science and technology* (pp. 495–520). https://onlinelibrary.wiley.com/doi/10.1002/9781118850220.ch21

Hintzer, K., Zipplies, T., Carlson, D. P., & Schmiegel, W. (2013). Fluoropolymers, Organic. In *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley. https://doi.org/10.1002/14356007.a11_393.pub2

Honeywell. (2021). *Blister packaging*. https://lifesciences.honeywell.com/us/en/applications/healthcare-packaging/blister-packaging

Hoshino, T., & Morizawa, Y. (2017). Chapter 5: Fluorinated specialty chemicals–Fluorinated copolymers for paints and perfluoropolyethers for coatings. In B. Ameduri & H. Sawada (Eds.), *Fluorinated polymers: Volume 2: Applications* (pp. 110–126). The Royal Society of Chemistry. https://pubs.rsc.org.en/content/ebook/978-1-78262-916-0

Hull, D. E. (1983). *Tetrafluoroethylene-propylene copolymer (Aflas): New technology, new uses*. Xenox Inc. http://www.allsealsinc.com/pdf2/Aflas1.pdf

Hull, D. E., Johnson, B. V., Rodricks, I. P., & Staley, J. B. (1997). THV fluoroplastic. In J. Scheirs (Ed.), *Modern fluoropolymers* (257ff.). Wiley & Sons.

Kojima, G., Kojima, H., & Tabata, Y. (1977). A new fluoroelastomer derived from tetrafluoroethylene and propylene. *Rubber Chemistry and Technology*, *50*(2), 403–412. https://doi.org/10.5254/1.3535154

Kojima, G., & Yamabe, M. (1984). A solvent soluble fluororesin for paint. *Journal of Synthetic Organic Chemistry, Japan*, *42*, 841–849.

Korinek, P. M. (1994). Amorphous fluoropolymers—A new generation of products. *Macromolecular Symposia*, *82*(1), 61–65. https://doi.org/10.1002/masy.19940820108

Kostal, J. (2016). Chapter 4: Computational chemistry in predictive toxicology: Status quo et quo vadis? In J. C. Fishbein & J. M. Heilman (Eds.), *Advances in molecular toxicology* (Vol. 10, pp. 136–186). Elsevier. https://doi.org/10.1016/B978-0-12-804700-2.00004-0

Lavallée, C. (2020). Section 4.16 Polymer processing additives (PPA). In J. Macnamara (Ed.), *Film extrusion manual—Process, materials, properties* (3rd ed., pp. 291–302). TAPPI Press. https://imisrise.tappi.org/TAPPI/Products/01/R/0101R360.aspx

Lipinski, C., Lombardo, F., Dominy, B., & Feeny, P. (2001). Experimental and computational approaches to estimate solubility and permeability in drug discovery and development settings. *Advanced Drug Delivery Reviews*, *46*(1–3), 3–26. https://doi.org/10.1016/s0169-409x(00)00129-0

Lohmann, R., Cousins, I., DeWitt, J., Glüge, J., Goldenman, G., Herzke, D., Lindstrom, A., Miller, M., Ng, C., Patton, S., Scheringer, M., Trier, X., & Wang, Z. (2020). Are fluoropolymers really of low concern for human and environmental health and separate from other PFAS? *Environmental Science and Technology*, *54*(20), 12820–12828. https://doi.org/10.1021/acs.est.0c03244

Marshall, J. 2017. Kalrez®-type perfluoroelastomers—Synthesis, properties and applications. In J. Scheir (Ed.), *Modern fluoropolymers* (pp. 349–358). John Wiley and Sons.

Ménard, Y., Ashtana, A., Patisson, F., Sesiecq, P., & Ablitzer, D. (2006). Thermodynamic study of heavy metals behaviour during municipal waste incineration. *Process Safety and Environmental Protection*, *84*(B4), 290–296.

Miller, M., Pelch, K., Reade, A., Soehl, A., Trier, X., Venier, M., Wagner, C., Wang, Z., & Blum, A. (2020). Scientific basis for managing PFAS as a chemical class. *Environmental Science & Technology Letters*, *7*(8), 532–543. https://doi.org/10.1021/acs.estlett.0c00255

Munekata, S. (1988). Fluoropolymers as coating materials. *Progress in Organic Coatings*, *16*, 113–134. https://www.sciencedirect.com/science/article/pii/0033065588800104

NY State Department of Environmental Conservation (DEC). (2021). *Norlite environmental sampling report*. https://www.dec.ny.gov/chemical/121118.html

Organisation for Economic Co-operation and Development (OECD). (1993). *OECD expert group on polymers. Third Meeting of the Experts on Polymers: Chairman's Report* (ENV/MC/CHEM/RD(93)4). April.

Organisation for Economic Co-operation and Development (OECD). (2009). *Data analysis of the identification of correlations between polymer characteristics and potential for health or ecotoxicological concern*. OECD Task Force on New Chemicals Notification and Assessment, Expert Group Meeting on polymers, March, 2007, Tokyo, Japan. https://www.oecd.org/env/ehs/risk-assessment/42081261.pdf

Organisation for Economic Co-operation and Development (OECD). (2021). *Reconciling terminology of the universe of per- and polyfluoroalkyl substances: recommendations and practical guidance*. Series on Risk Management No. 61. https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/CBC/MONO(2021)25&docLanguage=en

Ohkura, M., & Morizawa, Y. (2017). Fluoroplastics and fluoroelastomers–Basic chemistry and high-performance applications. In B. Ameduri & H. Sawada (Eds.), *Fluorinated polymers Volume 2: Applications*. RSC Polymer Chemistry Series No. 24. RSC. https://doi.org/10.1039/9781782629368

Orgalim. (2021). *Orgalim Position Paper on the restriction of PFAS*. https://orgalim.eu/position-papers/environment-orgalim-position-paper-restriction-pfas?&utm_campaign=Policy%20Brunch%20for%20FPP4EU%207%20February&utm_medium=email&utm_source=Mailjet

Park, E.-J., Park, I.-C., Lee, M. S., & Park, M. (2008). Preparation of cladding polymers for plastical optical fibers—Miscibility and interfacial adhesion of PMMA/THV blends. *Textile Science & Engineering*, *45*(6), 364–369. https://www.koreascience.or.kr/article/JAKO200806135610008.pa1ff8ge

Parker, R., & Blankenship, K. (2015). Fluoroethylene vinyl ether resins for high-performance coatings. In K. B. Tator (Ed.), *ASM handbook Volume 5B, Protective organic coatings*. ASM International. https://doi.org/10.31399/asm.hb.v05b.9781627081726

Performance Fluoropolymer Partnership of the American Chemistry Council (PFP). (2020). *Socio-economic assessment of the US fluoropolymer industry*. https://fluoropolymerpartnership.com/fluoropolymer-facts/socioeconomic-importance/

Polymer Industry Association (PIA). (2019). *Guide to the safe handling of fluoropolymer resins* (5th ed.). https://www.plasticsindustry.org/supply-chain/material-suppliers/fluoropolymers-division-fpd

Pro-K Fluoropolymer Group. (2018). *Recycling of fluoropolymers*. https://www.pro-kunststoff.de/assets/Merkbl%C3%A4tter%20und%20Co/FP%20TM-10-Recycling-of-fluoropolymers.pdf

Pro-K Fluoropolymer Group. (2021). *PFAS restriction—Proposal & request for exemption of fluoropolymers*. https://www.pro-kunststoff.de/fachwissen/pfas-restriction-proposal-und-request-for-exemtion-of-fluoropolymers.html

Resnick, P. R., & Buck, W. (1997). Teflon® AF amorphous fluoropolymers. In J. Scheirs (Ed.), *High performance polymers for diverse applications* (pp. 397–419). John Wiley & Sons.

Resnick, P. R., & Buck, W. H. (1999). Teflon® AF: A family of amorphous fluoeopolymers with extraordinary properties. In W. H. Properties, G. Hougham, P. E. Cassidy, K. Johns, & T. Davidson (Eds.), *Topics in applied chemistry, fluoropolymers* (pp. 25–33). Springer, New York, NY. https://doi.org/10.1007/b114560

Royal Society of Chemistry (RSC). (2021). *Risk-based regulation for per- and poly-fluoroalkyl substances (PFAS)*. https://www.rsc.org/globalassets/22-new-perspectives/sustainability/a-chemicals-strategy-for-a-sustainable-chemicals-revolution/pfas-policy-position-dec-2021.pdf

Rüdel, H., Körner, W., Letzel, T., Neumann, N., Nödler, K., & Reemtsa, T. (2020). Persistent, mobile and toxic substances in the environment: A spotlight on current research and regulatory activities. *Environmental Sciences Europe*, *32*, 5. https://doi.org/10.1186/s12302-019-0286-x

Ruwona and Henry. (2021). *PTFE: Persistence without hazard at environmentally relevant temperatures and durable by design*. Fluoros 2021, Providence, RI.

Satokawa, T. (Ed.) (1990). *Fluoropolymer handbook: PCTFE* (pp. 337–357). Nikkan-Kogyo-Shimbun.

Scheirs, J. (2007). *Modern fluoropolymers—High performance polymers for diverse applications*. John Wiley & Sons.

Schlipf, M., & Schwalm, T. (2014). *Closing the recycling loop, Up-cycling of end-of-life fluoroplastics*. Kunststoffe International. June. https://www.kunststoffe.de/en/journal/archive/article/up-cycling-of-end-of-life-fluoroplastics-841786.html

Science Center. (2021). *Energetic electrolysis: The potentials of hydrogen power*. http://www.sciencenter.org/climatechange/d/cart_activity_guide_energetic_electrolysis.pdf

Sha, B., Schymanski, E., Ruttkies, C., Cousins, I., & Wang, Z. (2019). Exploring open cheminformatics approach for categorizing per- and polyfluoroalkyl substances (PFAS). *Environmental Science: Processes & Impacts*, *21*, 1835–1851. https://doi.org/10.1039/C9EM00321E

Shell. (2020). *Leveraging maximum value from polymer processing aids in polyethylene blown film* [Educational White Paper]. https://www.shell.us/business-customers/shell-polymers/polyethylene-film.html

Solvay. (2021a). *PVDF design and processing guide*. https://www.solvay.com/sites/g/files/srpend221/files/2018-08/Solef-PVDF-Design-and-Processing-Guide_EN-v2.7_0.pdf)

Solvay. (2021b). *HalarECTFE design and processing guide*®. https://www.solvay.com/sites/g/files/srpend221/files/2018-07/halar-ectfe-design-and-processing-guide-en.pdf)

Solvay. (2021c). *HalarECTFE*®. https://www.solvay.com/en/brands/halar-ectfe

Solvay. (2022). *Innovating with non-fluorosurfactant technologies*. https://www.solvay.com/en/innovation/science-solutions/pfas

United Nations (UN). (2021). *United Nations sustainable development goals*. https://sdgs.un.org/goals

US Code of Federal Regulations (USCFR). (2022). *21 CFR 177.2600 Rubber articles intended for repeated use*. https://www.ecfr.gov/current/title-21/chapter-I/subchapter-B/part-177/subpart-C/section-177.2600

USEPA. (1992). *TCLP toxicity characteristic leaching procedure* (SW-846 Test Method 131). https://www.epa.gov/sites/default/files/2015-12/documents/1311.pdf

USEPA. (1997). *Polymer exemption guidance manual* (EPA-744-B-97-001). June.

USEPA. (2010). *Reviewing new chemicals under the Toxic Substances Control Act (TSCA) EPA's Review Process - Chemical categories used to review new chemicals under TSCA: TSCA New Chemicals Program (NCP) Chemical Categories*. Washington (DC): USEPA Office of Pollution Prevention and Toxics. [cited 2017 July 12]. http://www.epa.gov/oppt/newchems/pubs/npcchemicalcategories.pdf

USEPA. (2012). *Sustainable futures/P2 framework manual*. https://www.epa.gov/sustainable-futures/sustainable-futures-p2-framework-manual

USEPA. (2021a). *PFAS strategic roadmap: EPA's commitments to action 2021—2024*. https://www.epa.gov/system/files/documents/2021-10/pfas-roadmap_final-508.pdf

USEPA. (2021b). *PFAS national testing strategy*. https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/national-pfas-testing-strategy#:%7E:text=To%20protect%20human%20health%20and,PFAS%20chemicals%20to%20inform%20future

United States Federal Register (USFR). (1984). *Premanufacture notification for polymers* (Final Rule 49 FR 46066, 1984 Nov 21. FR-2439-1).

United States Federal Register (USFR). (1995). *Premanufacture notification exemptions; Revisions of exemptions for polymers* (Final rule 60 FR 16316. 1995 Mar 29. FRL-4929-8). Fed Regist *60*(60), 16316–16336. Environmental Protection Agency.

United States Federal Register (USFR). (2012). Polymers (b). 40 CFR Sect 723.250.

Van Cleeff, A. (1997). Fluoroelastomers. In J. Schiers (Ed.), *Modern fluoropolymers* (pp. 507–614). John Wiley & Sons.

Wallington, T. J., Andersen, M. P. S., & Nielsen, O. J. (2021). The case for a more precise definition of regulated PFAS. *Environmental Science: Processes & Impacts*, *23*(12), 1834–1838. https://doi.org/10.1039/D1EM00296A

Worm, A. T., & Grootaert, W. (2001). Fluorocarbon elastomers. *Encyclopedia of Polymer Science & Engineering*. Wiley. https://doi.org/10.1002/0471440264.pst137

Yamabe, M., Higaki, H., & Kojima, G. (1984). New fluoropolymer coatings. In G. D. Parfitt & A. V. Pastis (Eds.), *Organic coatings science and technology* (Vol. 7, pp. 25–39). Marcel Dekker.

Integrated Environmental Assessment and Management — Volume 14, Number 3—pp. 316–334

Received: 26 September 2017 | Returned for Revision: 16 January 2018 | Accepted: 30 January 2018

Critical Review

A Critical Review of the Application of Polymer of Low Concern and Regulatory Criteria to Fluoropolymers

Barbara J Henry,† Joseph P Carlin,† Jon A Hammerschmidt,† Robert C Buck,‡ L William Buxton,‡ Heidelore Fiedler,§ Jennifer Seed,|| and Oscar Hernandez#*

†WL Gore & Associates, Elkton, Maryland, USA
‡Chemours Company, Wilmington, Delaware, USA
§MTM Research Centre School of Science and Technology, Örebro University, Örebro, Sweden
||Risk Assessment Consultant, Alexandria, Virginia, USA
#Bergeson & Campbell, Washington, DC, USA

ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are a group of fluorinated substances that are in the focus of researchers and regulators due to widespread presence in the environment and biota, including humans, of perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). Fluoropolymers, high molecular weight polymers, have unique properties that constitute a distinct class within the PFAS group. Fluoropolymers have thermal, chemical, photochemical, hydrolytic, oxidative, and biological stability. They have negligible residual monomer and oligomer content and low to no leachables. Fluoropolymers are practically insoluble in water and not subject to long-range transport. With a molecular weight well over 100 000 Da, fluoropolymers cannot cross the cell membrane. Fluoropolymers are not bioavailable or bioaccumulative, as evidenced by toxicology studies on polytetrafluoroethylene (PTFE): acute and subchronic systemic toxicity, irritation, sensitization, local toxicity on implantation, cytotoxicity, in vitro and in vivo genotoxicity, hemolysis, complement activation, and thrombogenicity. Clinical studies of patients receiving permanently implanted PTFE cardiovascular medical devices demonstrate no chronic toxicity or carcinogenicity and no reproductive, developmental, or endocrine toxicity. This paper brings together fluoropolymer toxicity data, human clinical data, and physical, chemical, thermal, and biological data for review and assessment to show that fluoropolymers satisfy widely accepted assessment criteria to be considered as "polymers of low concern" (PLC). This review concludes that fluoropolymers are distinctly different from other polymeric and nonpolymeric PFAS and should be separated from them for hazard assessment or regulatory purposes. Grouping fluoropolymers with all classes of PFAS for "read across" or structure–activity relationship assessment is not scientifically appropriate. *Integr Environ Assess Manag* 2018;14:316–334. © 2018 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals, Inc. on behalf of Society of Environmental Toxicology & Chemistry (SETAC)

Keywords: Fluoropolymer International regulation Polytetrafluoroethylene Polymer of low concern PFAS

INTRODUCTION

The carbon–fluorine (C–F) bond is the strongest bond between C and another atom, instilling substances that contain a majority of C–F bonds with stability, inertness, and persistence (Banks et al. 1994). Per- and polyfluoroalkyl substances (PFAS) are a large group of highly fluorinated synthetic substances with diverse properties that have been used in a wide variety of industrial and consumer applications since the 1950s (Buck et al. 2011). Within the group are distinct substances with different properties: polymers and nonpolymers; solids, liquids, and gases; persistent and nonpersistent substances; highly reactive and inert substances; mobile and insoluble substances; and toxic and nontoxic chemicals.

The PFAS are a large, diverse group of substances that, in some respects, challenge easy distinction for assessment and management. A clearer understanding of the origin of PFAS found in the environment and assessment of their properties is needed to be able to determine which classes of PFAS require management action. Per- and polyfluoroalkyl substances must be assessed taking into account their differences in chemical, physical, thermal, and biological properties. A single, globally harmonized system for PFAS classification has not yet been defined, resulting in a lack of distinction between PFAS. As regulatory frameworks continue to evolve, such as the Regulation (EC) No 1907/2006 of the European

This article includes online-only Supplemental Data.

* Address correspondence to bhenry@wlgore.com

DOI: 10.1002/ieam.4035

NMOGA Exhibit D3

Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) (RC 2006), more work is needed to distinguish classes of PFAS to ensure that regulations are appropriate in scope and proportionality.

Two long-chain nonpolymer perfluoroalkyl acids (PFAAs), perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) (both PFAS), found widespread in the environment and living systems, led to regulatory assessment and management efforts in several countries (Buck et al. 2011; OECD 2017; USEPA 2017a). Management actions to curtail manufacture of long-chain PFAAs, including PFOS and PFOA, and substances that may degrade to form them (also known as "precursors") have been taken (EC 2006; ECHA 2015; USEPA 2017a). Both PFOS and PFOA have been determined by regulators to be persistent, bioaccumulative, and toxic (PBT) substances (EC 2006; ECHA 2015). A current concern is the potential for certain side-chain polymer PFAS to degrade in the environment to PFOS and PFOA or lower homologues (Liu and Mejia-Avendaño 2013). In addition, PFOS (a nonpolymeric perfluoroalkyl substance) and related substances have been listed as persistent organic pollutants (POPs) under Annex B of the Stockholm Convention (UNEP 2009), and PFOA and other related substances (UNEP 2011), as well as perfluorohexane sulfonic acid (PFHxS) and related substances are being evaluated for listing (UNEP 2017a). As a result, questions about the health and environmental safety of PFAS as a group have been raised (Scheringer et al. 2014; Blum et al. 2015).

These findings have prompted expanded regulatory interest and concern about PFAS as a group, spurring additional assessment and management actions. The German Environment Agency, Umweltbundesamt (UBA), published a proposal to implement new assessment criteria and procedures for identifying persistent (P), mobile (M), and toxic (T) substances under the European Union REACH chemical registration process (UBA 2017). The UBA has concluded that PM and/or PMT substances constitute "an irreversible threat to sources of drinking water and the quality of drinking water" in Germany. This has prompted the designation of PFAS substances as posing an "equivalent level of concern" under Article 57(f) of REACH and thereby has prompted the need for a new paradigm for chemical assessment and authorization. The Swedish Chemicals Agency, Kemikalieinspektionen (KEMI), announced agreement among 37 government agencies and research institutions in the European Union (EU) to expand cooperation to reduce the risks and increase the knowledge of PFAS, thereby endorsing the UBA view on the hazards posed by all PFAS substances (KEMI Swedish Chemicals Agency 2016). The KEMI announcement indicated that all perfluoralkyl substances should be considered as extremely persistent in the environment, and many are water soluble, mobile in soil, and likely to contaminate waterways and drinking water supplies. A risk assessment report prepared by KEMI is forthcoming (ChemNews 2016).

The PFAS are divided into 2 primary categories: nonpolymers and polymers (Figure 1). Figure 1 shows that these 2 categories are divided into 5 classes of PFAS. The fluoropolymer class of PFAS is the focus of the present paper. The nonpolymer category includes perfluoroalkyl substances and polyfluoroalkyl substances. The polymer category includes fluoropolymers, perfluoropolyethers, and side-chain fluorinated polymers. Polymers generally have very different physical, chemical, and biological properties than do nonpolymer chemical substances of low molecular weight. Precise criteria that distinguish polymers from nonpolymers have been established (OECD 1993).

There are distinct differences between the 5 classes of PFAS. For example, PFOA, in the class nonpolymer perfluoroalkyl substances, is small, mobile, and persistent; has been assessed and determined to be a PBT chemical (ECHA 2015); and is in the final stage for recommendation of listing as a POP under the Stockholm Convention (UNEP 2017b). Regulatory and industry management actions on PFOA include precursor substances that may degrade to form PFOA (USEPA 2017a). An example in the class of nonpolymer polyfluorinated substances, 8:2 fluorotelomer alcohol, is known to degrade under environmentally relevant conditions to form PFOA (Liu and Mejia-Avendaño 2013). It is therefore a precursor substance to PFOA and subject to regulatory management (Liu and Mejia-Avendaño 2013). Polymers derived from 8:2 fluorotelomer alcohol are examples of the side-chain fluorinated polymers class. These polymers may degrade to form PFOA and therefore are subject to regulatory management. Lastly, perfluoropolyethers class is a complex class of PFAS, which contains O linkages in the polymer backbone.

In the present paper, we address fluoropolymers, a class of PFAS polymers (Figure 1). Fluoropolymers are high molecular weight solid plastics that have been studied extensively.

The present paper brings together fluoropolymer toxicity data, human clinical data, and physical, chemical, thermal, and biological data for review and assessment to show that fluoropolymers satisfy widely accepted assessment criteria to be considered as "polymers of low concern" (PLC) and to show that fluoropolymers are distinctly different enough from other classes of PFAS to not be grouped with them for hazard assessment or regulatory purposes.

PERFORMANCE CHARACTERISTICS AND USES OF FLUOROPOLYMERS

Since the discovery of polytetrafluoroethylene (PTFE) in 1938 (Plunkett 1987), the use of fluoropolymers has grown considerably to take advantage of their unique physical–chemical, thermal, and biological properties. The 4 fluoropolymers addressed in the present paper, polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), ethylene tetrafluoroethylene (ETFE), and tetrafluoroethylene copolymers with perfluoroalkyl vinyl ethers (e.g., perfluoroalkoxy polymer, PFA), accounted for approximately 70% to 75% of the world fluoropolymer consumption in 2015 (IHS 2016). The representative fluoropolymer discussed in the present paper, PTFE, made up 58% (by weight) of 2015 worldwide fluoropolymer consumption (IHS 2016). Fluoropolymers are high molecular weight plastics with unique properties attributable to the strong C–F bonds, the strongest bond between C and another atom, making

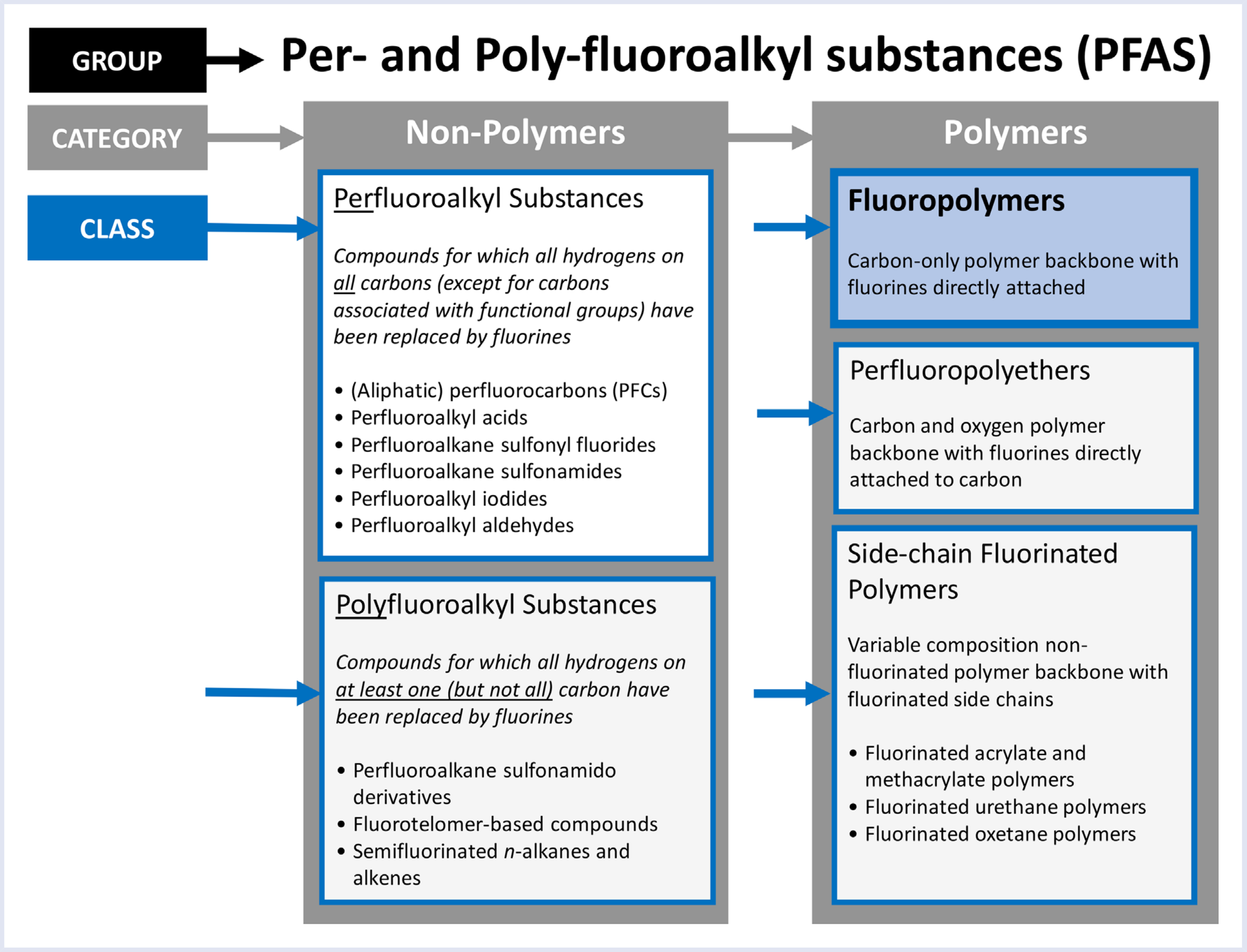


Figure 1. Per- and polyfluoroalkyl substances (PFAS).

them highly stable (Olabisi and Adewale 2015). Carbon atoms alone form the fluoropolymer backbone, each surrounded by an envelope of F atoms. Fluoropolymers are generally very high molecular weight (>100 000 Da); have high thermal, chemical, photochemical, oxidative, hydrolytic, and biological stability; have low flammability, neutral electrical charge, and resistance to degradation; have negligible residual monomers and low molecular weight oligomer content; have limited low molecular weight leachables; and have no reactive functional groups of concern (Gangal and Brothers 2015).

The unique properties of fluoropolymers include durability, mechanical strength, inertness, thermal stability in foreseeable use conditions, and resistance to chemical, biological, and physical degradation (Hougham et al. 1999). Table 1 shows performance characteristics required in various commercial fluoropolymer applications (Gangal and Brothers 2015; Dams and Hintzer 2016). For example, medical devices are successful when they are made from "biocompatible" biomaterials, that is, the material has the ability to perform with an appropriate host response in a specific situation (Williams 1987). The inertness of PTFE allows for its acceptance into the body. Moreover, PTFE flexibility and durability deliver mechanical integrity for the device's lifetime. The microstructure of PTFE can be modified to meet specific physiological needs (e.g., porous and open structure to facilitate tissue ingrowth), enhancing its utility in medical devices. In terms of end-use function, PTFE's inertness, physical properties (Ebnesajjad 2011), and the low level of residual monomer, oligomers, and low molecular weight leachables (Supplemental Data p 32–55) meet the requirements for low levels of contaminants and particulates in manufacturing environments essential for the food and beverage, pharmaceutical, medical, and semiconductor industries (Olabisi and Adewale 2015). Manufacturing applications requiring ultrapure high efficiency particulate air (HEPA) filtration use the finely controlled microporous PTFE membranes. Other components requiring a high degree of contamination control associated with patient care (e.g., dialysis tubing) also find the properties of PTFE essential. Durability in harsh conditions makes PTFE a superior material of choice in aerospace, environmental controls, energy production and storage, and electronics, as well as in technical apparel. The thermal stability of PTFE and FEP fluoropolymers provides improved fire safety risk over other polymers when used in plenums and structural

Table 1. Fluoropolymer functionality and commercial applications

Commercial application	Fluoropolymer characteristics									
	Durable		Inert		Functional			Stable		
	Mechanical strength	Low particulation	Resistance to chemicals	Nontoxic, biocompatible, biological degradation resistant	Flexibility	Friction resistance	Low dielectric constant	Low leachables	Resistance to photolysis, oxidation, hydrolysis	Stability
Aerospace	X	—	X	—	X	X	X	—	X	X
Automotive industry	X	—	X	—	X	X	X	—	X	x
Medical devices	X	X		X	X	X	—	X	X	X
Pharmaceutical manufacture	X	X	X	X	X	—	—	X	—	X
Consumer outdoor apparel	X	—		X	X	—	—	X	—	—
Technical clothing (military, firefighters, first responders, medical personnel)	X	—	X	X	X	X	—	X	X	X
Consumer electronics	X	—	X	—	X	X	X	—	X	X
Wireless communications	X	—	X	—	X	X	X	—	X	X
Satellite navigation systems	X	—	X	—	X	X	X	—	X	X
Semiconductor industry	—	X	X	—	—	—	X	X	—	—
Building construction	X	—	—	X	X	—	X	—	X	X
Energy production and storage	X	X	—	—	—	—	X	X	X	X
Food and beverage production	X	X	X	X	X	X	—	X	X	—
Food protection and packaging	X	X	X	X	X	—	—	X		—
Drinking water filtration	—	X	X	X	—	—	—	X	X	—
Environmental protection	—	X	X	X	—	—	—	X	X	X

geometries in aviation and standard building construction (Olabisi and Adewale 2015). In addition, chemical resistance to acids, bases, solvents, and chemical attack, combined with its unique conformable strength, makes PTFE an ideal coating for chemical process equipment, lining for process piping, sealants for gaskets and hoses, and fabricated parts for pumps, gears, and other mechanical parts that need this extreme resistance for functionality (Olabisi and Adewale 2015). The low dielectric constant of PTFE ensures the integrity of high speed–low signal loss systems as employed in the aerospace industry for flight controls, communication, and protection from extreme cold, moisture, and altitude changes (Dams and Hintzer 2016). These are lifesaving applications that are used in satellite systems for navigation, wireless communications, in-flight navigation, and shielding from electronic interference. Civil and military aviation depends on reliable performance of these systems for long service hours with minimal maintenance down times. In addition, PTFE provides reduced friction of moving parts (e.g., cable chains), preventing particulation during automated manufacturing in cleanroom environments (Dams and Hintzer 2016). This friction reduction is also uniquely beneficial in light load bearings, gears, cams, and other mechanical machine parts as well as in weaving fibers, yarns, and greases (Dams and Hintzer 2016).

ASSESSMENT OF POLYMERS

History

Prior to the mid-20th century, regulation of new chemical substances, mixtures, and polymers in general was very limited. National chemical inventories were created with notification requirements for new chemical substances, mixtures, and polymers. In the United States, new chemicals submitted to the US Environmental Protection Agency (USEPA) under the Toxic Substances Control Act (TSCA) (USC 1976) for addition to the US chemical inventory are reviewed for potential physical, chemical, and biological effects (environmental and mammalian), as well as for potential exposure to the environment and human populations. Over time, the USEPA regulatory scientists gained enough knowledge through the review of the thousands of data packages to develop tools to assist in the identification of physical–chemical properties, potential hazard, and potential exposure to assist in and expedite the chemical review and assessment process (Auer et al. 1990; Wagner et al. 1995; USEPA 2012; USEPA 2017b).

The predictive power and reliability of these approaches were tested and refined (Wagner et al. 1995). Over time, it was recognized that many of the physical–chemical properties, such as molecular weight, limit the ability of the chemical to cross the cell membrane and therefore limit its bioavailability. Further examination of general physical–chemical properties and their relationship to hazard potential of a given chemical led to the development of general principles or criteria for the identification of chemicals, including polymers, with low hazard potential. These criteria were developed for use by USEPA for its hazard evaluation of new polymers. The USEPA made this methodology available to the public to assist submitters interested in developing low hazard polymers (USEPA 1997a). In 1984, the USEPA published the polymer exemption rule to exempt low hazard polymers from certain notification requirements under the new chemicals program (USFR 1984). The polymer exemption rule incorporated the hazard criteria as part of the criteria to determine eligibility for exemption (USEPA 1997a, 2010).

The hazard criteria that support the PLC concept represent an extension of these principles and practices developed for (nonpolymeric) chemicals and rely heavily on physical–chemical properties that determine a chemical's bioavailability. In 1993, the Organisation for Economic Co-operation and Development (OECD) Expert Group on Polymers found that sufficient data existed to create a consensus document identifying the essential data elements to qualify a polymer as a PLC to human health and the environment (OECD 1993). By 2007, the OECD Expert Group on Polymers agreed that, "Polymers of low concern are those deemed to have insignificant environmental and human health impacts" (OECD 2009). Thus, there was agreement within the OECD that polymeric chemicals meeting these criteria have a low hazard potential. However, the integration of the criteria into a risk management framework may differ from country to country according to their individual regulatory mandate.

In a recent report commissioned by the European Commission (EC) (BIO by Deloitte 2015), the following countries agreed on the polymer properties predictive of adverse human health and environmental hazard: Australia, Canada, China, Japan, South Korea, Philippines, New Zealand, Taiwan, and the United States. Further, the report identified the eligibility criteria to be considered a PLC with respect to potential for adverse impact on health and the environment. The report also compiled existing polymer regulations outside the EU and proposed alternative options for EU polymer registration, including defining a category of a PLC and grouping polymers into families.

The PLC criteria are described in the following section. Note that there are some policy components, such as elemental composition, as well as the physical–chemical attributes, in the PLC criteria.

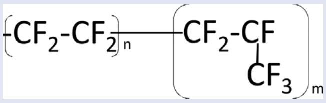
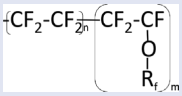
POLYMER OF LOW CONCERN CRITERIA

Here we describe each of the eligibility criteria for PLC and provide an assessment for the representative fluoropolymer PTFE. We will show that fluoropolymers, including PTFE, satisfy the widely accepted assessment criteria to be considered PLCs (Table 2) and therefore are considered to be of low hazard to human health and the environment.

Polymer composition

The polymer composition criterion requires structure and elemental composition of the polymer be described and identified (e.g., by Chemical Abstracts Service [CAS] number).

Table 2. Fluoropolymers and PLC criteria

	Fluoropolymers			
	PTFE	ETFE	FEP	PFA
Assessment criteria[a]	CAS 9002-84-0	CAS 25038-71-5, 68258-85-5	CAS 25067-11-2	CAS 26655-00-5, 31784-04-0
Structure	$-(CF_2-CF_2)_n-$	$-(CH_2-CH_2)_n-(CF_2-CF_2)_m-$	 $-(CF_2-CF_2)_n-(CF_2-CF(CF_3))_m-$	 $-(CF_2-CF_2)_n-(CF_2-CF(O-R_f))_m-$
Polymer composition (must have C, H, Si, S, F, Cl, Br, or I covalently bound to C)	Yes	Yes	Yes	Yes
Molecular weight	389 000–8 900 000[b,c]	—	—	—
($M_n > 1000$ Da and oligomer content $< 1\%$)	520 000–45 000 000[b,d]	530 000–1 200 000[e,f]	241 000–575 000[e,g]	200 000–450 000[e,h]
Molecular weight distribution MW ÷ number average M_n (M_n and heterogeneity of MW distribution indicate if majority are >1000 or <1000 Da, which could penetrate the cell)	2.3[i]	1.4–2.7[f]	1.55–2.09[g]	1.7[j]
Wt % oligomer (see Figure 2) (<5% for <1000 Da oligomers, <2% for <500 Da oligomers)	Negligible	Negligible	Negligible	Negligible
Ionic character (cationic polymers associated with aquatic toxicity; polycationic with adverse human health effect)	Neutral	Neutral	Neutral	Neutral
RFGs[k] (some highly reactive functional groups associated with adverse human health and ecotoxicology effects, e.g., acrylates, isocyanates, anhydrides, aziridines)	<1 (see section *Reactive functional groups and RFG ratio to MW*)	<1 (see section *Reactive functional groups and RFG ratio to MW*)	<1 (see section *Reactive functional groups and RFG ratio to MW*)	<1 (see section *Reactive functional groups and RFG ratio to MW*)
FGEW[k] (typical value) (the lower the FGEW, the more reactive the polymer and the higher the potential for health and environmental impact)	$>10^5–10^7$	$>10^5–10^6$	$>10^5$	$>10^5$
Low molecular weight leachables (MW < 1000 Da able to enter cell)	<1 ppm	No active leachables by USP class VI[l] (121 °C)	No active leachables by USP class VI[l] (121 °C)	No active leachables by USP class VI[l] (121 °C)
Residual monomers (monomers have lower MW than polymers; typically more hazardous than polymers)	<1 ppm	<50 ppb	<50 ppb	<50 ppb
Ratio of residual monomers to molecular weight (typical value) (more low MW monomer content per mole increases bioavailability and hazard potential)	$\sim 10^{-13}$ to 10^{-15}	$\sim 10^{-13}$ to 10^{-14}	$\sim 10^{-13}$	$\sim 10^{-13}$
Structural similarities to RFG of concern (increases potential risk of adverse effects)	None	None	None	None
Reference standard see also ISO 1133 (ISO 2011), ISO 12086 (ISO 2006)	ASTM D 4894 (ASTM 2015a), D 4895 (ASTM 2015b)	ASTM D 2116 (ASTM 2016a)	ASTM D 3159 (ASTM 2015c)	ASTM D 3307 (ASTM 2016b)

(*Continued*)

D3.7

Table 2. (*Continued*)

	Fluoropolymers			
	PTFE	ETFE	FEP	PFA
Assessment criteria[a]	CAS 9002-84-0	CAS 25038-71-5, 68258-85-5	CAS 25067-11-2	CAS 26655-00-5, 31784-04-0
Physical–chemical properties				
Water solubility (per USP 2011) (water solubility <10 mg/L showed generally low health concerns; 10 mL/L to 10000 mg/L had potential health concern)	Practically insoluble or insoluble (1×10^{-5} mg/L)	Practically insoluble or insoluble	Practically insoluble or insoluble	Practically insoluble or insoluble
Octanol–water partition coefficient, K_{OW} (higher K_{OW} associated with lipophilicity and a high potential to bioaccumulate or bioconcentrate)	NA	NA	NA	NA
Particle size (median mass aerodynamic diameter, MMAD, should be >5 μm)	100–500 μm (powders)	50–250 μm (powders)	50–250 μm (powders)	50–250 μm (powders)
	—	2–4 mm (pellets)	2–4 mm (pellets)	2–4 mm (pellets)
Stability				
Hydrolysis (breaking into $M_n < 1000$ Da increases hazard potential)	Stable	Stable	Stable	Stable
Light ($h\nu$) (breaking into $M_n < 1000$ Da increases hazard potential)	Stable	Stable	Stable	Stable
Oxidation (breaking into $M_n < 1000$ Da increases hazard potential)	Stable	Stable	Stable	Stable
Biodegradation (aerobic and anaerobic) (breaking into $M_n < 1000$ Da increases hazard potential)	Stable	Stable	Stable	Stable
Thermal stability at normal foreseeable use maximum continuous temp (°C) (breaking into $M_n < 1000$ Da increases hazard potential)	260	150	200	260
Meets PLC criteria[a] (Y/N)	Yes	Yes	Yes	Yes

ASTM = American Society for Testing and Materials; CAS = Chemical Abstracts Service; Da = dalton; ETFE = ethylene tetrafluoroethylene; FEP = fluorinated ethylene propylene; FGEW = functional group equivalent weight; ISO = International Organization for Standardization; MMAD = median mass aerodynamic diameter; M_n = number average molecular weight; MW = molecular weight; MWD = molecular weight distribution; OECD = Organisation for Economic Co-operation and Development; PFA = perfluoroalkoxy polymer; PFPE = perfluoropolyether; PLC = polymer of low concern; PTFE = polytetrafluoroethylene; PVDF = polyvinylidene fluoride; PVF = polyvinyl fluoride; RFG = reactive functional groups; USEPA = US Environmental Protection Agency; USP = US Pharmacopeia.

[a] See OECD 2009 and BIO by Deloitte 2015 for details on characteristics of a "polymer of low concern."

[b] Molecular weight is number average molecular weight.

[c] Berry and Peterson 1951; Doban et al. 1956.

[d] Suwa et al. 1973.

[e] Molecular weight is weight average molecular weight.

[f] Tuminello et al. 1993.

[g] Tuminello 1989.

[h] Putnam 1986.

[i] Chu et al. 1989.

[j] Frick et al. 2012.

[k] For definition of reactive functional group; lists of low-, moderate-, and high-concern functional groups; and FGEW limits, see USEPA Polymer Exemption Guidance Manual (USEPA 1997b), BIO by Deloitte 2015 (p 191–192), and USEPA 2010. See Supplemental Data.

[l] In the USP<88> testing for "class VI," 2 g of the plastic (e.g., FEP, ETFE, or PFA) were extracted at 121 °C in: 1) 0.9% sodium chloride solution, 2) sesame oil, NF, 3) alcohol saline, and d) polyethylene glycol. The acute systemic toxicity and intracutaneous reactivity tests were conducted with those extracts. The intramuscular implantation was conducted with the plastic. Passing these 3 tests indicates that any leachables were not released in concentrations capable of causing these adverse effects, but does not result in a quantitative concentration of leachables. (See USP 2018.)

Note: The following are not addressed in this paper: PFPEs, side-chain fluorinated polymers, fluoroelastomers, PVF, and PVDF.

DOI: 10.1002/ieam.4035

Molecular weight, number average molecular weight, MW distribution, and % oligomer <1000 Da

The number average molecular weight (M_n) and oligomer content are the most commonly used criteria for PLC assessment. The EU assessment report (BIO by Deloitte 2015) states that the "most potential health concern polymers have a number average molecular weight, Mn, < 1000 Da and oligomer content >1%." The higher the oligomeric content, the more likely a polymer is to be a health or ecotoxicological (OECD 2009, p 9). In fact, when comparing the potential health concern of polymers with varying percent oligomer content, "…the distribution of potential health concern polymers showed an increased incidence of higher oligomer content that began at 5% for <1000 Da and 2% for <500 Da oligomeric content" (OECD 2009, p 24).

Molecular weight (MW) is an important predictor of biological effect because very large molecules (>1000–10 000 Da) are too large to penetrate cell membranes (Supplemental Data in Beyer 1993, p 14). Because large molecular weight polymers cannot enter the cell, they cannot react with "target organs," such as the reproductive system, and are not bioavailable. "Therefore, as the M_n of a polymer increases, a reduced incidence of potential health concern effects might be expected" (OECD 2009, p 20).

An additional PLC consideration is the weight percent oligomers <1000 Da. Oligomers may be composed of, for example, dimers, trimmers, and tetramers, meaning they have 2-, 3-, and 4-monomer units, respectively. The EU report (BIO by Deloitte 2015) concluded that most potential health concern polymers have M_n of <1000 Da and oligomer content of >1%: "…the distribution of potential health concern polymers showed an increased incidence of higher oligomer content that began at 5% for <1000 Da and 2% for <500 Da oligomeric content" (OECD 2009, p 24).

Molecular weight distribution (MWD), also known as "polydispersity index," measures the heterogeneity of size of polymer molecules in a polymer. The MWD is an important parameter for predicting potential biological effects of polymers because although M_n may be a large value, low MW oligomers <1000 Da may be present, which could penetrate the cell.

Electrical charge (ionic character)

Electrical charge or ionic character can be anionic, cationic, amphoteric, or nonionic. Specifically, cationic polymers have been associated with aquatic toxicity (Auer et al. 1990; USEPA 1997a). Polycationic polymers that are water soluble or dispersible are of concern due to adverse human health (inhalation) effects (NICNAS 2016).

Reactive functional groups and RFG ratio to MW

A "reactive functional group" (RFG) is defined as an atom or associated group of atoms in a chemical substance that is intended or can be reasonably anticipated to undergo facile chemical reaction (USFR 2012). Some highly reactive functional groups (or a high ratio of RFGs per mole) have been associated with adverse human health and ecotoxicology (e.g., acrylates, methacrylates, isocyanates, anhydrides, aziridines) (USEPA 2010). Methods have been demonstrated to identify the functional end groups on fluoropolymers (Pianca et al. 1999).

The functional group equivalent weight (FGEW) is used to determine if the RFGs in a polymer are substantially diluted by polymeric material to allow the polymer to be a PLC (USEPA 1997b). The FGEW of a polymer is defined as the ratio of the M_n to the number of functional groups in the polymer. It is the weight of a polymer that contains 1 formula weight of the functional group. The FGEW is used as an indication of the degree of reactivity of the polymer; the lower the FGEW, the more reactive the polymer and the higher the potential for health and environmental impact (OECD 2009, p 10).

Low MW leachables

Low MW leachables are chemical molecules, either inorganic or organic, that migrate (i.e., leach) out of the polymer. These could be residual monomers or oligomers resulting from incomplete polymerization processes, surface residues, or other chemicals used in the manufacturing processes (e.g., initiators, catalysts, chain transfer agents, surfactants). Chemical analysis, by techniques such as thermal gravimetric analysis (TGA), gas chromatography mass spectrometry (GC-MS), or liquid chromatography mass spectrometry (LC-MS) are used to identify low MW leachables.

Low MW leachables are critically important to the potential for a polymer to affect health and the environment, given that they may be able to migrate out of the polymer and cross cell membranes to potentially react with biomolecules. In a report to the EU (BIO by Deloitte 2015) the polymer policies for 10 countries around the world, including the EU REACH handling of polymers, were reviewed. The report concluded that "Polymers with <1% MW <1000 Da and low water extractivity are not able to cause systemic effects which are toxicologically or ecotoxicologically relevant."

Monomers, by nature, are reactive. Unreacted monomer left in a polymer may migrate out of the polymer to react with biomolecules to cause potential adverse effects. Regulatory authorities (BIO by Deloitte 2015) and the OECD Expert Group on Polymers (OECD 2009) agree that the residual monomer content of a polymer is critical to determining if it qualifies to be a PLC.

Particle size

Particle size is also a PLC criterion. Particles that are small enough to reach the deep lung upon inhalation are often associated with adverse health effects. Therefore, to qualify as a PLC, median mass aerodynamic diameter (MMAD) of the polymer particle size should be greater than 5 μm.

Structural and elemental composition

In the United States, Chemical Categories of Concern are the result of the review of new chemicals by the USEPA under the TSCA (see https://www.epa.gov/reviewing-new-chemicals-under-toxic-substances-control-act-tsca/chemical-categories-used-review-new). New chemicals submitted to the USEPA under the TSCA for addition to the US chemical inventory are reviewed for potential chemical, physical, and biological effects (environmental and mammalian). The USEPA groups Premanufacture Notice (PMN) chemicals with shared chemical and toxicological properties into categories, enabling both PMN submitters and USEPA reviewers to benefit from the accumulated data and past decisional precedents, allowing reviews to be facilitated. The categories describe the molecular structure, boundary conditions such as MW, equivalent weight, the log of the octanol–water partition coefficient, log P, or water solubility, and standard hazard (mammalian and ecological) and (environmental) fate tests to address concerns. The categories include chemicals for which sufficient history has been accumulated so that hazard concerns and testing recommendations vary little from chemical to chemical within the category. (See Supplemental Data, p 30, for details on USEPA's chemical categories.)

Elemental composition

The elemental composition is a factor in the assessment of the eligibility of polymers for reduced notification requirements. The exclusion of polymers under this step is not a conclusion of hazard but a determination that the elemental composition does not fall within the parameters of the polymer set under which this rule was formulated, and consequently, these polymers would have to follow the standard notification and review process. These elemental requirements differ across jurisdictions as covered in the report to the EU on global regulatory approaches to polymer assessment (BIO by Deloitte 2015). For example, in the EU under REACH it is proposed that polymers composed from among these elements, covalently bound to C, have reduced hazard: H, N, O, Si, S, F, Cl, Br, or I (BIO by Deloitte 2015). In contrast, the USEPA Polymer Exemption Rule states that a polymer is eligible for reduced agency review when it has at least 2 of the following elements: C, H, O, N, S, or Si (USFR 1995).

Water and lipid solubility and the octanol–water partition coefficient

Water solubility is the extent to which a compound will dissolve in water. According to the OECD 2009 meeting of the Expert Group on Polymers, polymers with "negligible" water solubility, or those described as "hydrophobic" have been represented with a water solubility of 0.000001 mg/L (1×10^{-6} mg/L; assigned arbitrarily) (OECD 2009). That is equivalent to 1 ppt, a very conservative definition.

Based on the data set studied, the OECD Expert Group on Polymers concluded "A higher proportion of polymers with intermediate water solubility values (10 mL/L–10 000 mg/L) displayed potential health concern. Polymers with water solubility <10 mg/L showed generally low health concerns" (OECD 2009, p 10). Although not a solubility metric, a polymer capable of absorbing its weight in water was associated with increased inhalation cancer risk in rats (OECD 2009).

The octanol–water partition coefficient (K_{OW}) is another criterion to assess chemicals and their environmental and health impact. The K_{OW} is a physical–chemical property at equilibrium to represent the lipophilic or hydrophilic nature of a chemical, the distribution of a compound in octanol, representing the lipophilic nature, to its solubility in water, representing the aqueous nature. The higher the K_{OW}, the more lipophilic the compound. Typically, a $K_{OW} > 5000$ or a log $K_{OW} > 5$ means high lipophilicity and, thus, a high potential to bioaccumulate or bioconcentrate. Numerous studies showed that K_{OW} was useful for correlating structural changes of drug chemicals with the change observed in some biological, biochemical, or toxic effect (LaGrega et al. 2010). It has been found to be related to water solubility, soil or sediment adsorption coefficients, and bioconcentration factors for aquatic life. According to the Stockholm Convention, a bioconcentration factor of >5000 and a log $K_{OW} > 5$ is used as a criterion for bioaccumulation.

Stability

Stability is resistance to physical, chemical, or biological transformation. Loss of stability in the polymer breaks it down into smaller pieces, producing low MW species. As was previously described in the Polymer of Low Concern section under the *Molecular weight, number average molecular weight, MW distribution, and % oligomer <1000 Da* heading, molecules with M_n <1000 Da are capable of crossing cell membranes, making unstable polymers potentially hazardous to health and the environment.

Abiotic stability

Polymers are stable; monomers are not. Abiotic degradation may involve sunlight, water, or oxygen. Photochemical transformation is a reaction involving the radiation energy of sunlight (ultraviolet radiation) that may break a bond in a molecule to change it to another chemical entity. Hydrolytic degradation of polymers is another potential way to break the polymer bonds, creating smaller oligomers that may be bioavailable. Chemical oxidation is a reaction involving the loss of electrons from 1 atom to another.

Biotic stability: aerobic, anaerobic, and in vivo

Biotic stability is assessed by whether or not the polymer is degraded by microorganisms under oxygenated (aerobic) or anoxic (anaerobic) conditions; in vitro and in vivo stability studies demonstrate this. In vivo biodegradation involves the breaking of the polymer bonds by the action of bacteria, enzymes, and oxidants within the organism.

Thermal stability

Thermal stability of a polymer can be assessed when used as intended under normal, foreseeable use conditions or in extreme temperatures during disposal, such as by incineration. Thermal stability testing may involve Thermal Gravimetric Analysis (TGA), which determines mass loss over time and temperature of a test substance.

ASSESSMENT OF FLUOROPOLYMERS ACCORDING TO PLC CRITERIA

Characteristics of a PLC have been described in the preceding section. These criteria represent the combined

DOI: 10.1002/ieam.4035

experience and knowledge of global regulatory authorities on factors demonstrated to be predictive of health and environmental hazards of polymers (OECD 2009; BIO by Deloitte 2015). Four fluoropolymers were assessed according to the PLC criteria. The results are summarized in Table 2, and an expanded discussion on specific criteria is provided in the remainder of this section.

Polymer composition

Fluoropolymers satisfy the PLC criterion of polymer composition. Polytetrafluoroethylene is a homopolymer of tetrafluoroethylene (TFE). Polytetrafluoroethylene can be a homopolymer (1 monomer) or it can be a modified homopolymer containing TFE widely and not more than 1% of another fluoromonomer (see ASTM 2015). Polytetrafluoroethylene contains only C and F having a $–CF_2–$ backbone terminated on both ends of each polymer chain with $–CF_3$. In unique cases, based on production method and ingredients used, commercial PTFE may have end groups that contain O, H, N, or S, depending on the initiator or chain transfer agent used in polymerization (Pianca et al. 1999). Polytetrafluoroethylene meets the compositional criterion to be a PLC.

Molecular weight, M_n, MWD, and % oligomer <1000

Fluoropolymers satisfy the PLC criterion of MW, M_n, MWD, and % oligomer <1000. Fluoropolymers are practically insoluble in water and all organic solvents. Therefore, standard MW methods are not applicable for fluoropolymers like PTFE and have been replaced by standardized indirect methods that use specific gravity and melt flow index to determine MW of PTFE and fluoropolymers (see Supplemental Data, p 27–28). Standard Specific Gravity (SSG) and Melt Flow Rate (MFR) are more conveniently and frequently used with fluoropolymers rather than rheological and dynamic light scattering methods (Chu et al. 1989; Starkweather and Wu 1989; Tuminello 1989; Tuminello et al. 1993). Polytetrafluoroethylene has an M_n of 500 000 to 9 000 000 Da (Berry and Peterson 1951; Doban et al. 1956; Suwa et al. 1973; Putnam 1986; Chu et al. 1989; Tuminello 1989; Tuminello et al. 1993; Frick et al. 2012). Therefore, PTFE, as a very high molecular weight polymer, cannot cross cell membranes, is not bioavailable, and cannot bioaccumulate or be toxic (see Supplemental Data, p 14). High molecular weight fluoropolymers, such as PTFE, therefore meet the PLC criterion for having MW that prevents them from entering the cells. Polytetrafluoroethylene has negligible (<<1%) oligomeric content (Starkweather and Wu 1989), as does FEP (Figure 2.) In summary, fluoropolymers are high molecular weight polymers with narrow MWD and negligible oligomer content.

Reactive functional groups and RFG ratio to MW

Fluoropolymers satisfy the PLC criterion of RFGs and RFG ratio to MW. Polytetrafluoroethylene most typically has a terminal $–CF_3$ group that is not an RFG. When this is not the case, the most common terminal group is –COOH, which is categorized by the USEPA as a low-concern functional group. In unique cases, based on production method and ingredients used, PTFE may have end groups that may contain O, and H, N, or S, depending on the initiator or chain transfer agent used in polymerization. Fluoropolymers have a very high MW, which yields an FGEW on the order of 10^5 or more, well beyond the FGEW threshold of concern.

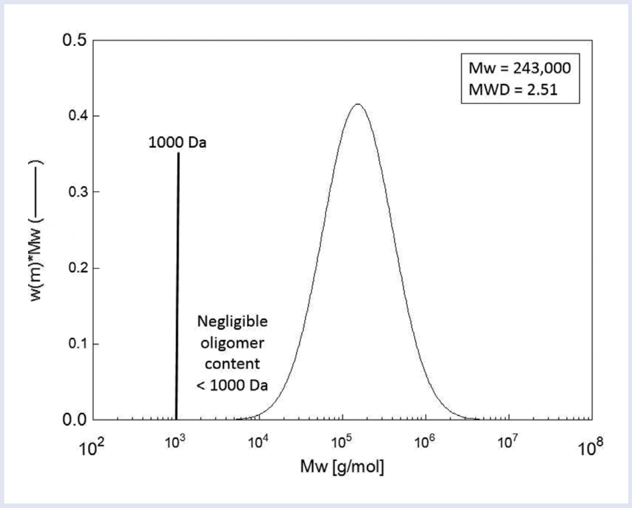


Figure 2. A fluorinated ethylene propylene (FEP) fluoropolymer molecular weight distribution from a rheological study. MW = molecular weight; MWD = molecular weight distribution.

Low MW leachables

Fluoropolymers satisfy the PLC criterion of low MW leachables. Concentration of leachables from fluoropolymers, particularly PTFE "fine powder" (ASTM [2015] 4895-16 Type I fine powder definition), are typically very low (<1 ppm) (see Supplemental Data). This finding can be explained by the sensitivity of the PTFE polymerization reaction to contamination and is due to the postpolymerization processing steps aggressively exercised to wash out residuals and drive off volatiles. In order to achieve high MW polymerization of TFE, all traces of telogenic H- or Cl-bearing impurities must be removed (Ebnesajjad 2011; Supplemental Data).

In the analysis done on PTFE (see Supplemental Data, p 32), residual TFE monomer was not detected in PTFE resin by headspace GC-MS with a limit of detection of 1 ppm. In addition, publicly available analytical data from independent industry authorities demonstrate that TFE is not detected in finished articles made from fluoropolymers at detection limits down to about 0.01 ppm wt/wt (SPI 2005). Table 3 compares the molecular weight and the 8-h time weighted average (TWA) (American Conference of Governmental Industrial Hygienists [ACGIH], threshold limit value [TLV]), for monomers used to make fluoropolymers (ACGIH 2010). The TWAs are the exposure levels to which a worker could be exposed in an 8-h shift without adverse effects. The monomers have significantly lower MW, have lower TWAs, and are reactive. Note that the fluoropolymers are high MW, have no TWAs, and are inert. Table 3 illustrates that polymers do not have the same health hazards or MWs as their monomers.

Table 3. Fluoropolymer and monomer molecular weight and TLV data

Substance	CAS Nr	Molecular weight	ACGIH TLV 8-h TWA
Monomer: TFE	116-14-3	100	2 ppm
Monomer: Ethylene	74-85-1	28	200 ppm
Monomer: HFP	116-15-4	150	0.1 ppm
Monomer: PPVE	1623-05-8	266	200 ppm (vendor limit)
Polymer: PTFE	9002-84-0	389 000–45 000 000	None
Polymer: ETFE	25038-71-5, 68258-85-5	530 000–1 200 000	None
Polymer: FEP	25067-11-2	241 000–575 000	None
Polymer: PFA	26655-00-5, 31784-04-0	200 000–450 000	None

ACGIH = American Conference of Governmental Industrial Hygienists (ACGIH 2010); CAS = Chemical Abstracts Service; ETFE = ethylene tetrafluoroethylene; FEP = fluorinated ethylene propylene; HFP = hexafluoropropene; PFA = perfluoroalkoxy polymer; PPVE = perfluoropropylvinyl ether; PTFE = polytetrafluoroethylene; TFE = tetrafluoroethylene; TLV = threshold limit value; TWA = time weighted average.

Elemental composition

Fluoropolymers meet the widely accepted elemental composition criterion (BIO by Deloitte 2015). The USEPA, in updating its Polymer Exemption Rule, which applies to new polymers only, changed some review procedures to address certain side-chain fluorinated polymers that may degrade into small, mobile, and persistent substances (USFR 2010). This has contributed to confusion regarding the assessment of fluoropolymers. The exclusion of polymers under this step is not a conclusion of hazard, but a determination that the elemental composition does not fall within the parameters of the polymer set under which this rule was formulated, and consequently, these polymers would have to follow the standard notification and review process.

When USEPA updated the polymer exemption rule in 2010, the agency excluded polymers containing $-CF_3$ or larger chains that are covalently bound to C. The agency's rationale for the change was "...because the Agency has receiving information which suggests that polymers containing PFAS (perfluoroalkyl sulfonates) or PFAC (perfluoroalkyl carboxylates) may degrade and release fluorochemical residual compounds in the environment. Once released, PFAS or PFAC are expected to persist in the environment, may bioaccumulate, and may be highly toxic..." (USFR 2006).

Although USEPA recognized that PFAS and PFAC chemicals with longer C chain lengths (C7 and longer) may be of greater concern, it stated that there is insufficient evidence at this time, however, to definitively establish a lower C chain length limit to meet the "will not present an unreasonable risk" finding, which is the determination necessary to support an exemption under section 5(h)(4) of TSCA. The USEPA believes that it is possible for polymers containing these other types of perfluoroalkyl moieties to also degrade over time in the environment, thereby releasing the perfluoroalkyl moiety (USFR 2006).

The updated USEPA polymer exemption definition in 2010, summarized in the Objective and Rationale section for the Final Rule, may imply that new fluoropolymers with pendant or terminal –CF3 groups, such as FEP, do not meet the polymer exemption eligibility for reduced PMN reporting (USFR 2010). However, the summary definition in USFR (2010) lacks critical context found in the preamble to the Final Rule, which elaborates the conditions that would be necessary to exclude a perfluoro chemical from the polymer exemption:

- The first condition is cited above, "...polymers containing PFAS (perfluoroalkyl sulfonates) or PFAC (perfluoroalkyl carboxylates)..." where the C or S atom is an integral part of the polymer molecule; and
- the second condition notes that, polymers containing fluorotelomers or "...perfluoroalkyl moieties that are covalently bound to either a carbon or sulfur atom where the carbon or sulfur atom is an integral part of the polymer molecule can be attached to the polymers using conventional chemical reactions."

For the PFAS and PFAC as described by USEPA, the agency offers a clarification about the nature of the linkage, stating "How these materials are incorporated into the polymer is immaterial (they may be counter ions, terminal/end capping agents, or part of the polymer backbone)" (USFR 2010). The key characteristic is the presence of a –CF3 group that is attached to, or forms part of, the polymer backbone and "this link (between the polymer backbone and the –CF3 group) is susceptible to degradation and cleavage." (USFR 2010). Thus, in USEPA's review, the presence of –CF3 group is important because it is a structural alert to consider potential degradation products. The USEPA will make a determination whether the potential degradation of the polymer in question presents an unreasonable risk to health and the environment under TSCA. As shown in Table 2, these fluoropolymers are not subject to degradation.

Water and lipid solubility and the octanol–water partition coefficient

Fluoropolymers, such as PTFE, are not soluble in octanol or water. Therefore, it is not possible to measure or calculate a

K_{OW}. Because solubility in octanol is predictive of lipid solubility, PTFE cannot dissolve in cell membrane lipids to gain access to cellular contents, nor is it small enough to enter the cell due to its very high MW. Because PTFE cannot enter the cells, it is not capable of bioaccumulation or bioconcentration in aquatic life.

Stability

Under normal, foreseeable uses, fluoropolymers are stable. Stability is resistance to physical, chemical, or biological transformation. Loss of stability in the polymer breaks it down into smaller pieces, producing low MW species. Molecules with M_n <1000 Da are capable of crossing cell membranes, making unstable polymers potentially hazardous to health and the environment. Fluoropolymers, in general, have exceptional chemical and thermal stability; that is why they are so unique and useful. This is due to very strong C–F bonds that are stable under even extreme conditions (Gangal and Brothers 2015). Polytetrafluoroethylene is inert and chemically resistant to all solvents except molten alkali metals, chlorine trifluoride, and oxygen difluoride. Polytetrafluoroethylene, as a representative fluoropolymer, has the best chemical resistance of all currently known polymers and is insoluble in all known solvents, including water (Drobny 2006).

Abiotic stability

Polymers are stable; monomers are not. Photochemical transformation is a reaction involving the radiation energy of sunlight (ultraviolet radiation) that may break a bond in a molecule to change it to another chemical entity. Although PTFE will rapidly degrade in ionizing radiation (e.g., gamma radiation or high energy electron-beam radiation), it is resistant to photolysis (Drobny 2006). Photoinduced reactions with fluoropolymers do not occur. In addition, hydrolysis is a reaction involving the breaking of a bond in a molecule using water. The fluorine envelope surrounding the C backbone of PTFE is very hydrophobic. Fluoropolymers, such as PTFE, are hydrolytically stable, water resistant, and are not subject to hydrolysis catalyzed degradation (Arkles 1973). Finally, chemical oxidation is a reaction involving the loss of electrons from one atom to another. Because the C–F bond is one of the strongest known, and F is the most electronegative element, the C–F bond is thermodynamically stable, unfavorable to lose electrons (i.e., to oxidize) (Arkles 1973).

Biotic stability: aerobic, anaerobic and in vivo

Fluoropolymers like PTFE are biologically inert and not degraded by microorganisms under oxygenated (aerobic) or anoxic (anaerobic conditions); in vitro and in vivo studies demonstrate this. In vivo degradation involves the breaking of the polymer bonds due to bacteria and other enzymes and oxidants. For example, PTFE hernia patches explanted from patients and examined by scanning electron microscopy, attenuated total reflectance Fourier transform infrared spectroscopy, modulated differential scanning calorimetry, and optical microscope showed no degradation in vivo (King et al. 2013).

Thermal stability

Fluoropolymers, when used as intended under normal, foreseeable use conditions as specified in Table 2 (or "continuous processing temperature") are thermally stable (Puts et al. 2014). The fluoropolymer industry has provided significant information on appropriate use of fluoropolymers (SPI 2005). Thermal gravimetric analysis determines mass loss over time and temperature of a test substance. Polytetrafluoroethylene is one of the most thermally stable polymers. Polytetrafluoroethylene's continuous processing temperature is 260 °C (SPI 2005). This means that PTFE could remain for decades at 260 °C and not decompose (SPI 2005 see percent mass lost per hour at maximum continuous processing temperature).

Outside of normal, foreseeable use conditions (also known as "misuse"), when fluoropolymers are held at temperatures above their recommended processing temperatures, they degrade. Upon decomposition, fluoropolymers generate volatile degradation products (SPI 2005). At 450 °C, the decomposition of PTFE "only proceeds at a rate on the order of one percent per hour. It is not until considerably above the polymer first-order transition temperature (329 °C) that substantial decomposition is observed" (Arkles and Bonnett 1974). As the temperatures increase above recommended processing temperatures, the rate of generation rises and may sufficiently degrade the polymer to produce hazardous gaseous byproducts and polymer (particulate) fume fever (SPI 2005). Temperature, availability of O, the physical form of the polymer article, and the residence time at elevated temperature factor into the ultimate nature of the decomposition products (SPI 2005), mainly fluoroalkenes, hydrogen fluoride, oxides of C, and lower molecular weight fluoropolymer particulates. For PTFE, TFE is the principle gaseous product observed at temperatures near 330 °C. See Supplemental Data for additional information regarding overheating PTFE.

PRODUCT-SPECIFIC REGULATORY REQUIREMENTS

Certain product-specific regulations, such as those for medical devices and food contact for the United States and the EU, require the development of additional data beyond what is required to conduct a PLC evaluation. The following text will discuss food contact requirements for the United States and the EU, and medical device requirements.

Data requirements for food, pharmaceutical, and medical device applications

There are country-specific data requirements for fluoropolymer use in food, pharmaceutical, and medical device applications because the intended use of these products has the potential to directly or indirectly introduce the product into the human body. An extensive fluoropolymer data set has been developed by W.L. Gore for these uses. The clinical history of the safe implantation of more than 40 million PTFE medical devices over 40 y, extensive toxicity data, preclinical data, and chemical extractables and migration testing confirmed that fluoropolymers are not bioavailable. Although the data requirements have evolved over time for contacting food, pharmaceuticals, or use in medical devices, the data (some of which are provided in the present article, the Supplemental Data for the present paper, regulatory submissions, and product literature) confirm the conclusion that fluoropolymers are safe for these intended uses and support the conclusion that fluoropolymers should be considered PLCs.

Polymer of low concern data and US and European Union food contact requirements

In general, the data required to support a PLC determination are helpful, but insufficient to qualify a material for food contact use. Submissions to the US Food and Drug Administration (USFDA) to support new food contact substances require extensive data submissions, including, for example, the nature and amount of nonvolatile extractives (USFDA 2017). Fluoropolymers, however, are not new substances in applications where they come in contact with food and have longstanding acceptance by regulators. In the United States, the USFDA is responsible for regulation of materials that come in contact with food and are considered "indirect food additives," specifically polymers (USFR 2016a). Food storage or food packaging materials, such as the fluoropolymers PTFE, FEP, and PFA, are "perfluorocarbon resins" acceptable for use by application and material type, provided they meet the extractable limits specified in the regulation (USFR 2016b).

Similarly, the European Food Safety Agency (EFSA) provides recommendations to the European Commission (EC) within the EU for the regulation of food contact materials, requirements for their evaluation, and authorization of acceptable uses (EC 2004). Polymer clearance is based in part upon the fact that polymers will not migrate into food due to their high molecular weight. The EU focuses on potential low molecular weight moieties, such as residual monomers and leachables, rather than on the polymer itself. The EU food contact regulation requires that monomers, other starting substances, and additives used to produce food contact polymers should be risk assessed and authorized (EU 2011). The regulation lists authorized substances that are permitted to have food contact (EU 2011). This regulation also sets the specific migration limit (SML), which is the maximum permitted amount of substance in food that has been determined not to pose a risk to human health, specifically for individual chemicals (e.g., monomer) (EU 2011). Note that these limits exist whether or not the substance is present in the food contact material (FCM). The monomers, other starting substances, and additives used to produce fluoropolymers for food contact (e.g., PTFE, FEP, and PFA) have been authorized for food contact uses. Representative SMLs for these monomers, additives, and starting substances relevant for fluoropolymers are given in the Supplemental Data (p 14).

Polymer of low concern data and medical device regulatory requirements

Satisfaction of the PLC criteria is insufficient to satisfy medical device requirements. Formal biocompatibility evaluations are required by the USFDA and other global regulatory authorities to support submissions for approval of medical devices and pharmaceuticals (e.g., combination products, such as drug-eluting stents or prefilled single-dose syringes). The International Organization for Standardization (ISO) 10993 Biocompatibility of Medical Devices standards describe a broad array of biocompatibility tests that require consideration for each new device or significant changes to existing devices (ISO 2009). Over the years, medical devices containing PTFE (or expanded PTFE) have been evaluated using ISO 10993 and US Pharmacopeia (USP) Class VI standards (USP 2011) and have been determined to be biocompatible in their intended uses.

The ISO 10993 standards provide guidance for evaluation of the biological response to a medical device. The USFDA, as well as most international regulatory agencies, recognizes and uses ISO 10993 standards to guide safety evaluations of medical devices submitted for their approval. Requirements to demonstrate the biocompatibility of medical devices are set forth in ISO 10993-1, and regulatory authority–specific requirements (e.g., PMDA 2003; USFDA 2016). In addition, country pharmacopeial organizations also specify testing required for biological reactivity of drugs (e.g., US Pharmacopiea, EU Pharmacopiea, Japan Pharmacopiea). The ISO requirements are categorized by the nature of body contact (e.g., mucosal membrane, circulating blood, tissue, bone, dentin) and duration of contact ($<$24 h, $\geq$1 d $\leq$30 d, $>$30 d). Depending on the nature and duration of contact, requirements include cytotoxicity, irritation, sensitization, implantation, acute–subchronic–chronic systemic toxicity, material-mediated pyrogenicity, hemocompatibility (e.g., hemolysis, thrombogenicity, and complement activation), genotoxicity (in vitro and in vivo), carcinogenicity, and developmental toxicity. (See Supplemental Data p 15 for a list of ISO 10993 biocompatibility tests.)

MEETING PLC CRITERIA PRECLUDES A FINDING THAT A CHEMICAL IS OF HIGH CONCERN

Just as regulatory frameworks have mechanisms to identify materials of low concern such as PLCs, they also have mechanisms to identify chemicals of high concern. For example, under REACH, a mechanism exists to identify substances of very high concern (SVHCs). Having demonstrated that fluoropolymers like PTFE should be considered PLCs, we will also demonstrate that these fluoropolymers cannot be SVHCs under REACH, do not meet the PM and PMT criteria proposed by UBA, and do not meet the criteria for listing as a POP under the Stockholm Convention.

Fluoropolymers and EU REACH SVHC, CMR, PBT, vPvB, and endocrine disrupting chemical (EDC) criteria

According to the European Chemicals Agency (ECHA), SVHCs are defined in Article 57 of Regulation (EC) Nr 1907/2006 ("the REACH Regulation") (EC 2006) and include substances that are

- "Carcinogenic, mutagenic or toxic to reproduction (CMR), meeting the criteria for classification in category 1 or 2 in accordance with Directive 67/548/EEC. This directive was replaced in beginning of 2009 by the new EU regulation (EC) No 1272/2008 on classification, labeling and packaging of chemical substances and mixtures, the so-called CLP Regulation. According to the new CLP Regulation these substances shall be classified as 1a or 1b."
- "Persistent, Bioaccumulative and Toxic (PBT) or very Persistent and very Bioaccumulative (vPvB) according to the criteria in Annex XIII of the REACH Regulation."
- "Identified, on a case-by-case basis, from scientific evidence as causing probable serious effects to human health or the environment of an equivalent level of concern as those above (e.g., EDCs)."

Under REACH, polymer substances are not registered, but the monomers they are composed of are registered, and the registration must be supported by data submissions that are tiered on the basis of tonnage (see EC 2006, Annex VII). The REACH definition of polymer includes materials with as few as 3 repeating units. But such a small molecule would not meet common industry standard definitions for fluoropolymers (ASTM 2015). It is highly unlikely that fluoropolymers meeting the PLC criteria would exhibit the criteria of an SVHC under REACH. Fluoropolymer data developed for other regulatory needs support the predictive value of the PLC assessment criteria and demonstrate the low hazard potential of this class of PFAS. Due to their physical–chemical properties, PLCs are not bioavailable to cause toxicity or to bioaccumulate. Toxicity study data on PTFE in the Supplemental Data (p 15–27), for example, demonstrate a lack of toxicity, including genotoxicity. Although fluoropolymers are persistent, they are not bioaccumulative or toxic and therefore do not meet the PBT criteria.

Fluoropolymers and German UBA–proposed PMT criteria

As regulatory frameworks continue to evolve, more work is needed in the area of PFAS classification to ensure that regulations are appropriate in scope and proportionality. Although some well-known PFAS would qualify as PM or PMT substances as proposed by the UBA (2017), fluoropolymers do not possess these characteristics. Although fluoropolymers are highly stable (persistent), they do not meet the criteria to be mobile or toxic. To demonstrate this point, PTFE, a high molecular weight fluoropolymer and a member of the PFAS group, is assessed (in the last 4 paragraphs of this section) according to the proposed UBA criteria (UBA 2017).

Briefly, the changes to PM and/or PMT assessment proposed by UBA address applicability, persistence, mobility, and toxicity. The UBA proposes an initial step involving assessment of the chemical composition of a substance to determine if the substance is within the applicability domain of the proposed new assessment criteria. The UBA notes that currently only identifiable organic and organometallic chemicals are considered, and purely inorganic substances or substances of unknown or variable compositions, complex reaction products, or biological material are excluded (UBA 2017).

With respect to persistence, UBA proposes that the criterion for persistence be the same as in Annex XIII of REACH, which considers degradation half-lives in marine water, fresh- or estuarine water, marine sediment, and soil as part of the PBT/very persistent, very bioaccumulative (vPvB) assessment criteria; these degradation half-life criteria range from 40 to 180 d. The UBA proposes that a substance meets the persistent criterion if the degradation half-life in marine water at pH 6 to 8 and 12 °C is higher than 60 d, the half-life in fresh- or estuarine water at pH 6 to 8 and 12 °C is higher than 40 d, the half-life in marine sediment at pH 6 to 8 and 12 °C is higher than 180 d, the half-life in fresh- or estuarine water sediment at pH 6 to 8 and 12 °C is higher than 120 d, or the half-life in soil at pH 6 to 8 and 12 °C is higher than 120 d.

The UBA proposes that the mobility criterion for a persistent chemical should be determined on the basis of 2 considerations. First, the water solubility of a substance at pH 6 to 8 and 12 °C must be greater than or equal to 150 μg/L, and the log K_{OC} at pH 6 to 8 and 12 °C must be less than or equal to 4.5. The UBA notes that the mobility criterion should be applied only to substances that have fulfilled the criterion for persistence.

Lastly, with respect to toxicity, UBA proposes a 5-part test for involving data to understand if the substance is carcinogenic, germ cell mutagenic, or toxic for reproduction; if there is other evidence of chronic toxicity; and if there is evidence for effects on or via lactation. The derived no adverse effect level (DNEL) must be less than or equal to $9\,\mu g \cdot kg^{-1} d^{-1}$. The UBA notes that the first 2 considerations are the same criteria defined in Annex XIII of REACH as part of the PBT/vPvB assessment criteria regarding human health. The next 2 criteria specifically address concerns for drinking water exposure and are based on Regulation EC No 1272/2008 (EC 2008) and Cramer class II (Cramer et al. 1978) for substances exhibiting moderate or low biological activity, respectively. The DNEL criterion is based on Kalberlah et al. (2014).

Regardless of the arguments concerning the scientific foundation and credibility of the changes proposed by UBA to REACH PM and PMT assessment criteria, the central question with respect to PTFE is whether chemical-specific assessment would lead to an outcome different from that assuming PTFE behaved similarly to other PFAS substances. Polymers, including fluoropolymers, are different from non-polymeric chemicals and may be regulated differently. Because of these differences, it is recognized that some data requirements may not be applicable to polymers (EU 2011) For example, as we have shown, the physical–chemical criteria of PLC are predictive of lack of hazard.

With respect to applicability, PTFE is not a substance currently registered under REACH because it meets the REACH definition of a polymer substance: "a molecule that contains a sequence of at least 3 monomer units, which are covalently bound to at least one other monomer unit or other reactant" (EC 2006). However, because PTFE is an identifiable organic substance, the proposed UBA framework for assessment using the proposed PMT criteria would be applicable. Further, PTFE is highly stable and persistent in the environment. It is resistant to thermal degradation, being stable for decades at temperatures up to 260 °C (SPI 2005); is stable in terms of hydrolysis, oxidation, and light (Brydson 1999); and is stable in terms of anaerobic and aerobic degradation (King et al. 2013). Therefore, PTFE would fulfill the UBA's proposed persistence criterion.

In contrast, PTFE is practically insoluble in water and, therefore, is not mobile in the environment. Using the descriptive solubility table for the USP (2011), the water solubility of PTFE would be classified as practically insoluble (1×10^{-5} mg/L or 0.01 μg/L) to very slightly soluble (1×10^{-4} mg/L or 0.1 μg/L) (USP 2011). The mobility of PFTE is 1000 to 10 000× lower than UBA's proposed mobility criterion. Therefore, PTFE does not fulfill UBA's proposed mobility criterion and would not be classified as a PM or PMT substance.

A similar negative finding for PTFE pertains to toxicity. The average molecular weight of PTFE is too large for the polymer to cross a cell membrane, which means it is not bioavailable or toxic. Polytetrafluoroethylene has been tested extensively in the United States and European Union to assess commercial applications for food contact and global medical device regulations (see Supplemental Data for additional details). Results demonstrate the absence of toxicity. Therefore, PTFE does not fulfill UBA's proposed toxicity criterion and would not be classified as a PM or PMT substance (Table 4).

Fluoropolymers and the Stockholm Convention POP criteria

In addition to country and regional regulations, there are global legally binding instruments, such as the United Nations Environment Programme–administered conventions on chemicals and waste (UNEP 2001), such as the Stockholm Convention on Persistent Organic Pollutants. The Convention aims to eliminate POPs by eliminating their production, reducing their use, or limiting their use through a cradle-to-grave approach. For the listing of new chemicals into the Convention, numeric or other criteria have been set for the screening of proposed compounds. Stockholm Convention Criteria (annex D) are compared to those of the USEPA, EU REACH, and the UBA-proposed PMT (Table 4). Fluoropolymers meet the persistence criterion only, not the bioaccumulative, toxic, or mobile criteria.

Fluoropolymers satisfy widely accepted criteria to be considered PLCs. Their physical–chemical properties prevent bioavailability, bioaccumulation, toxicity, and degradation. They have negligible monomer, oligomer, and leachable content and no reactive functional groups with high toxicity. These comparisons of PLC and various regulatory assessment criteria demonstrate that, in the realm of PFAS, high molecular weight fluoropolymers like PTFE have vastly different properties than do other PFAS, and therefore, they are truly a separate class of materials that must be assessed on their own merits as has been done here. They also underscore the value of a global regulatory definition of a polymer.

FUTURE WORK

It is important to acknowledge that the manufacture and end-of-life phases of the fluoropolymer life cycle are not the subject of the present paper. The following reflections are provided on how these may be explored in future work. Fluoropolymer manufacture includes fluoromonomers and a wide array of initiators, catalysts, et cetera, including polymer production aids, some of which are fluorosurfactants (non-polymer PFAS) (see Supplemental Data, p 8, for more information about them). Historically, perfluorocarboxylic acids such as PFOA and perfluorononanoic acid (PFNA) were used as polymer production aids in the manufacture of fluoropolymers. They are no longer used by leading global fluoropolymer manufacturers (USEPA 2017a), who are now using alternative substances such as fluorinated polyether carboxylates (see Supplemental Data Table S2). The toxicological and environmental properties (e.g., persistence, bioavailability, and mobility) of these alternatives are very important. Future work should delve into fluoropolymer manufacture and describe the safety, health, and environmental management practices and controls employed; should describe the applicable regulations; and should assess substances used in fluoropolymer manufacture, their human health and environmental attributes, and their mass balance.

At end-of-life when a fluoropolymer has fulfilled its intended use and will be disposed of, the fate of fluoropolymers should be investigated further. Although there are sufficient data to demonstrate that fluoropolymers such as PTFE do not degrade in the environment or release substances of toxicological or environmental concern (Hintzer and Schwertfeger 2014), the downstream, end-of-life process of incineration merits future work. For instance, at temperatures above 450 °C, PTFE begins to degrade, releasing hazardous substances such as hydrofluoric acid. There are published studies on the incineration of fluoropolymers under normal, foreseeable municipal waste incinerator conditions targeting specific analytes (Taylor 2009). Presently, most legislation addresses the release of hydrogen fluoride (HF) as the only critical parameter; limit values are for stack emissions (e.g., EU 2000). Future work should investigate incineration under a range of relevant foreseeable use conditions to determine more comprehensively the substances formed and their amounts. Such an incineration study is underway with results to be published upon completion (W.L. Gore 2017). In addition, the practice of the open burning of fluoropolymers, or for that matter of any polymer, is unacceptable and unsafe. Responsible incineration of fluoropolymers, adhering to regulatory guidelines, at the end of their life cycle is appropriate.

DOI: 10.1002/ieam.4035

D3.16

Table 4. Comparison of United States, Stockholm Convention, EU REACH, and German Criteria

Criterion	United States[a]	Stockholm Convention[b]	REACH[c,d]	Germany[d,e]
Persistence (half-life)				
P	Water, soil, sediment > 60 d	Water >60 d	Marine water > 60 d	Same as REACH
		Soil, sediment >180 d	Estuarine water > 40 d	
			Fresh or estuarine sediment or soil > 120 d	
vP	Water, soil, sediment > 180 d		Marine, fresh, estuarine H_2O > 60 d	
			Marine, fresh, or estuarine sediment > 180 d	
			Soil > 180 d	
Bioaccumulation				
B	Aquatic BCF > 1000	Aquatic BCF or BAF > 5000	BCF > 2000	
		Log $K_{OW} > 5$		
vB	BCF > 5000		BCF > 5000	
Toxicity				
	Fish	Toxic or ecotoxic	Long-term aquatic NOEC or EC10 < 0.01	1) Carcinogenic, germ cell mutagenic, or toxic for reproduction[d];
	Low > 10 mg/L	(No numeric criteria)	Classified as carcinogen category 1A or 1B; mutagen 1A or 1B; reproductive toxin 1A, 1B, or 2[d]	2) other evidence of chronic toxicity[d]; and
	Moderate 0.1 mg/L–10 mg/L			3) evidence for effects on or via lactation[d].
	High < 0.1 mg/L			4) DNEL[f] $\leq 9\,\mu g \cdot kg^{-1}d^{-1}$
			Specific target organ toxicity (STOT RE 1 or 2) upon repeated (chronic) exposure)[d]	
Long-range transport (potential for)		Long-range transport (potential for): Presence through monitoring or modeled data; $t_{1/2}$ (air): 2 d		
Mobility				Mobility: water solubility at pH 6–8, 12 °C, must be ≥150 µg/L, and the log K_{OC} at pH 6–8, 12 °C must be ≤4.5.

BAF = bioaccumulation factor; BCF = bioconcentration factor; DNEL = derived no adverse effect level; EU = European Union; M = mobile; P = persistent; REACH = Registration, Evaluation, Authorisation and Restriction of Chemicals; STOT RE = specific target organ of toxicity repeat exposure; T = toxic; v = very.

[a] USEPA 1999.

[b] UNEP 2001

[c] ECHA 2014

[d] EC 2008

[e] UBA 2017

[f] Barlow 2005; Kalberlah et al. 2014.

Recycling, reuse, and closed loop systems are alternative options at the end of life. Recent work has shown, on a small scale, the ability to convert fluoropolymers back to their monomers for capture (Schlipf 2014; Invertec 2017). This approach to a closed loop economy for fluoropolymers merits additional work and discussion, as does the recycling and reuse of melt-processable fluoropolymers, such as FEP.

CONCLUSIONS

The present review has brought together fluoropolymer toxicity data, human clinical data, and physical–chemical characteristics, using PTFE as an example to show that fluoropolymers satisfy the widely accepted regulatory assessment criteria to be considered as PLCs. Fluoropolymers are high molecular weight, have narrow molecular weight distribution, and have negligible oligomer content and organic and inorganic leachables. Data show that fluoropolymers have thermal, chemical, photochemical, hydrolytic, and biological stability. Polytetrafluoroethylene has been extensively tested to comply with US and EU food contact and global medical device regulations (e.g., USFDA, CFDA, Korea MFDS, Japan PMDA), including ISO 10993 biocompatibility testing and preclinical animal testing. Toxicology studies on PTFE demonstrate the absence of acute or subchronic systemic toxicity, irritation, sensitization, local toxicity on implantation, in vitro and in vivo genotoxicity, hemolysis, complement activation, or thrombogenicity. The data presented demonstrate that the fluoropolymer class of PFAS is well defined, meets PLC criteria, and should be considered as distinctly different from other classes of PFAS. The grouping of all PFAS together is not supported by the scientific data.

Acknowledgment—The authors would like to thank Laura Hoch and Joel Tickner of the University of MA Lowell for comments on this manuscript; Yasuhiko Matsuoka of AGC Chemicals Americas, Inc.; Mary MaloneyHuss, Greg Hannon, Paul Fisher, David Einum, Catherine Parmeter and Terry Zitzelberger of W.L. Gore for technical assistance; John Jones of W.L. Gore for chemical analyses; Terrie Stike of W.L. Gore for manuscript preparation. We would also like to thank the editors and reviewers for their comments to improve this paper.

Disclaimer—BJ Henry, JP Carlin, and JA Hammerschmidt are employees of W.L. Gore, a global manufacturer of products made with fluoropolymers. RC Buck and LW Buxton are employees of The Chemours Company, a global manufacturer of fluoroproducts. O Hernandez, former Director of the Risk Assessment Division in the USEPA Office of Pollution Prevention and Toxics, is an employee of Bergeson and Campbell, a W.L. Gore contractor. J Seed, former Deputy Director of the Risk Assessment Division in the USEPA Office of Pollution Prevention and Toxics, is an independent risk assessment consultant to W.L. Gore. H Fiedler is a professor of Chemistry at the MTM Research Centre in the School of Science and Technology at Örebro University in Örebro, Sweden. Hernandez and Seed were retained and compensated by W.L. Gore & Associates, Inc., to assist in writing this paper. W.L. Gore & Associates, Inc., the Chemours Company, and the MTM Research Centre School of Science and Technology, Örebro University, Örebro, Sweden donated data and employee time to support this work.

Data Accessibility—All data and information used in this manuscript have been made available in tabulated form (Tables 1–4) by the authors and are included in the paper and the Supplemental Data.

SUPPLEMENTAL DATA

The Supplemental Data contains descriptive and more detailed information as highlighted in the paper.

Figure S1. Where does polytetrafluoroethylene (PTFE) come from?

Figure S2. Fluoropolymer primer: polytetrafluoroethylene (PTFE) polymerization scheme.

Figure S3. Fluoropolymer primer: polytetrafluoroethylene (PTFE) finishing scheme.

Figure S2. A fluorinated ethylene propylene (FEP) fluoropolymer molecular weight distribution from a rheological study.

Table S1. Polytetrafluoroethylene (PTFE) polymerization and post polymerization aids

Table S2. Alterative fluoropolymer processing aids: Sources of data

Table S3. Solubility table from USP 34 NF 29 General Notices, Section 5.3.0, p 6

Table S4. European Union (EU) specific migration limits (SMLs) for monomers in representative fluoropolymers

Table S5. Biocompatibility tests, conditions, and acceptance criteria results for expanded polytetrafluoroethylene patch

Table S6. US Environmental Protection Agency's (USEPA's) chemical categories of concern, 2010

REFERENCES

[ACGIH] American Conference of Governmental Industrial Hygienists. 2010. TLVs and BEIs: Threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati (OH): American Conference of Governmental Industrial Hygienists.

Arkles B. 1973. Recycling polytetrafluoroethylene in polymer science and technology. In: Guillet J, editor. Polymers and ecological problems, Vol. 3. New York (NY): Plenum. p 122.

Arkles B, Bonnett R. 1974. Method for the depolymerization of polytetrafluoroethylene, US 3832411A.

[ASTM] American Society for Testing and Materials. 2015a. ASTM D3159-15, Standard specification for modified ETFE fluoropolymer molding and extrusion materials.

[ASTM] American Society for Testing and Materials. 2015b. ASTM D4894, Standard specification for polytetrafluoroethylene (PTFE) granular molding and ram extrusion materials.

[ASTM] American Society for Testing and Materials. 2016a. ASTM D2116-16, Standard specification for FEP-fluorocarbon molding and extrusion materials.

[ASTM] American Society for Testing and Materials. 2016b. ASTM D3307-16, Standard specification for perfluoroalkoxy (PFA) resin molding and extrusion materials.

[ASTM] American Society for Testing and Materials. 2016c. ASTM D4895–16, Standard specification for polytetrafluoroethylene (PTFE) resin produced from dispersion.

Auer CM, Nabholz JV, Baetcke KP. 1990. Mode of action and the assessment of chemical hazards in the presence of limited data: Use of structure-activity relationships (SAR) under TSCA, Section 5. *Environ Health Perspect* 87:183–197.

Banks RE, Smart BE, Tatlow J. 1994. Organofluorine chemistry: Principles and commercial applications. New York (NY): Springer. 644 p.

Barlow S. 2005. Threshold of toxicological concern (TTC): A tool for assessing substances of unknown toxicity present at low levels in the diet. Brussels (BE): ILSI Europe. ILSI Europe Concise Monograph Series.

Berry KL, Peterson JH. 1951. Tracer studies of oxidation—Reduction polymerization and molecular weight of "Teflon" tetrafluoroethylene resin. *J Am Chem Soc* 73:5195–5197.

Beyer EC. 1993. Gap junctions. *Int Rev Cytol* 137:2.

BIO by Deloitte. 2015. Technical assistance related to the review of REACH with regard to the registration requirements on polymers Final report prepared for the European Commission (DG ENV), in collaboration with PIEP.

Blum A, Balan SA, Scheringer M, Trier X, Goldenman G, Cousins IT, Diamond M, Fletcher T, Higgins C, Lindeman AE, et al. 2015. The Madrid statement on poly- and perfluoroalkyl substances (PFAS). *Environ Health Perspect* 123:A107–A111.

Brydson JA. 1999. Plastics materials. 7th ed. Oxford (UK): Butterworth Heinemann. 920 p.

Buck RC, Franklin J, Berger U, Conder JM, Cousins IT, de Voogt P, Jensen AA, Kannan K, Mabury SA, van Leeuwen SPJ. 2011. Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins. *Integr Environ Assess Manag* 7(4):513–541.

ChemNews. 2016 Jul 7. Sweden's Kemi issues interim report on PFAS. Chemical Watch (Global Risk and Regulation News).

Chu B, Wu C, Buck W. 1989. Light scattering characterization of poly-(tetrafluoroethylene). PTFE in perfluorotetracosane: Molecular weight distribution and solution properties. *Macromolecules* 22:831–837.

Cramer GM, Ford RA, Hall RL. 1978. Estimation of toxic hazard—A decision tree approach. *Food Cosmet Toxicol* 16(3):255–276.

Dams R, Hintzer K. 2016. Industrial aspects of fluorinated oligomers and polymers. In: Ameduri B, Sawada H, editors. Fluorinated polymers, Vol 2: Applications. London (UK): Royal Society of Chemistry. p 1–31.

Doban RC, Knight AC, Peterson JH, Sperati CA. 1956. The molecular weight of polytetrafluoroethylene. Paper presented at 130th Meeting of American Chemical Society; 1956 Sep; Atlantic City, NJ. p 9S.

Drobny JG. 2006. Fluoroplastics. Shropshire (UK): Rapra Technology. p 12.

Ebnesajjad S. 2011. Introduction to fluoropolymers. In: Kutz M, editor. Applied plastics engineering handbook. New York (NY): Elsevier. p 49–60.

[EC] European Commission. 2004. Regulation (EC) No 1935/2004 of the European Parliament and of the Council of 27 October 2004 on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC. [cited 2017 July 12]. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02004R1935-20090807&from=EN

[EC] European Commission. 2006. Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). [cited 2017 July 12]. https://echa.europa.eu/regulations/reach/legislation

[EC] European Commission. 2008. Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 (Text with EEA relevance). [cited 2017 July 12]. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32008R1272

[ECHA] European Chemicals Agency. 2014. Guidance on information requirements and chemical safety assessment. Chapter R.11: PBT/vPvB assessment version 2.0 November 2014. [cited 2017 July 12]. https://echa.europa.eu/documents/10162/13632/information_requirements_r11_en.pdf/a8cce23f-a65a-46d2-ac68-92fee1f9e54f

[ECHA] European Chemicals Agency. 2015. Opinion of the Committee for Risk Assessment and Opinion of the Committee for Socio-economic Analysis on an Annex XV dossier proposing restrictions of the manufacture, placing on the market or use of a substance within the EU. [cited 2017 July 12]. https://echa.europa.eu/documents/10162/13641/rest_pfoa_compiled_opinions_en.pdf/2f0dfce0-3dcf-4398-8d6b-2e59c86446be

[EU] European Union. 2000. Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste.

[EU] European Union. 2011. European Union Guidance on Regulation (EU) No 10/2011 on plastic materials and articles intended to come into contact with food as regards information in the supply chain available on the food safety part of the website of the European Commission, on the page concerning the legislation on Food Contact Materials. [cited 2017 July 12]. http://ec.europa.eu/food/safety/chemical_safety/food_contact_materials/legislation/index_en.htm

Frick A, Sich D, Heinrich G, Stern C, Schlipf M. 2012. Classification of new melt-processable PTFE: Comparison of emulsion- and suspension-polymerized materials. *Macromol Mater Eng* 297:329–341.

Gangal SV, Brothers PD. 2015. Perfluorinated polymers. In: Kirk-Othmer encyclopedia of chemical technology. New York (NY): Wiley. p 1–68.

Hintzer K, Schwertfeger W. 2014. Fluoropolymers – Environmental aspects. In: Smith Jr DW, Iacano ST, Iyer SS, editors. Handbook of fluoropolymer science and technology. New York (NY): Wiley. p 495–520.

Hougham G, Cassidy PE, Johns K, Davidson T. 1999. Topics in applied chemistry. Fluoropolymers 2: Properties. New York (NY): Springer. 408 p.

IHS Markit. 2016. Fluoropolymers chemical economics handbook. Freedonia Group.

Invertec. 2017. Pilot project: Recycling of fluoropolymers (PTFE). [cited 2017 July 12]. https://www.invertec-ev.de/en/projects/environmental-care/ptfe-recycling/

[ISO] International Organization for Standardization. 2006. ISO 12086-1:2006 Plastics – Fluoropolymer dispersions and moulding and extrusion materials. Part 1: Designation system and basis for specifications.

[ISO] International Organization for Standardization. 2009. ISO 10993-1: Biological evaluation of medical devices. Part 1: Evaluation and testing in the risk management process. Geneva (CH).

[ISO] International Organization for Standardization. 2011. ISO 1133-1:2011 Plastics — Determination of the melt mass-flow rate (MFR) and melt volume-flow rate (MVR) of thermoplastics. Part 1: Standard method.

Kalberlah F, Oltmanns J, Schwartz MA, Baumeister J, and Stiffler A. 2014. Guidance for the precautionary protection of raw water destined for drinking water extraction from contaminants regulated under REACH. Dessau-Roßlau (DE): Umweltbundesamt (UBA). Report FKZ 371265416.

Kemi Swedish Chemicals Agency. 2016. Strategy for reducing the use of highly fluorinated substances, PFASs: Interim report as part of a Government assignment. Report 11/16. [cited 2017 July 12]. https://www.kemi.se/global/rapporter/2016/report-11-16-strategy-for-reducing-the-use-of-higly-fluorinated-substances-pfas.pdf

King MW, Gupta BA, Guidoin R. 2013. Biotextiles as medical implants:15. Vascular prostheses for open surgery. Cambridge (UK): Woodhood. p 434–484.

LaGrega M D. Buckingham PL, Evans JC. 2010. Hazardous waste management. 2nd ed. Long Grove (IL): Waveland. 1232 p.

Liu J, Mejia-Avendaño S. 2013. Microbial degradation of polyfluoroalkyl chemicals in the environment: A review. *Environ Int* 61:98–114.

[NICNAS] National Industrial Chemicals Notification and Assessment Scheme. 2016. NICNAS Handbook - Guide for importers and manufacturers of industrial chemicals in Australia. Sydney (AU). [cited 2017 July 12]. http://webarchive.nla.gov.au/gov/20161017033100/https://www.nicnas.gov.au/regulation-and-compliance/nicnas-handbook

[OECD] Organisation for Economic Co-operation and Development. 1993. OECD Expert Group on Polymers. Third Meeting of the Experts on Polymers: Chairman's Report [ENV/MC/CHEM/RD(93)4]; 1993 Apr; Paris (FR).

[OECD] Organisation for Economic Co-operation and Development. 2009. Data analysis of the identification of correlations between polymer characteristics and potential for health or ecotoxicological concern. OECD Task Force on New Chemicals Notification and Assessment, Expert Group Meeting on Polymers; 2007 Mar; Tokyo, Japan. Paris (FR).

[OECD] Organisation for Economic Co-operation and Development. 2017. OECD portal on per and poly fluorinated chemicals. Country Information section. Paris (FR). [cited 2017 July 12]. http://www.oecd.org/chemicalsafety/portal-perfluorinated-chemicals/

Olabisi O, Adewale K. 2015. Handbook of thermoplastics. 2nd ed. Boca Raton (FL): CRC.

Pianca M, Barchiesi E, Esposto G, Radice S. 1999. End groups in fluoropolymers. *J Fluorine Chem* 95:71–84.

Plunkett RJ. 1987. The history of polytetrafluoroethylene: Discovery and development. In: Seymour RB, Kirshenbaum GS, editors. High performance polymers: Their origin and development. New York (NY): Elsevier. p 261–266.

[PMDA] Japan Pharmaceutical and Medical Device Agency, Ministry of Health, Labour and Welfare. 2003. Basic principles of biological safety evaluation required for application for approval to manufacture (import) medical devices. Tokyo (JP). PFBS/ELD (Iyakushin) Notification No. 0213001. 2003 Feb 13.

Putnam RE. 1986. Development of thermoplastic fluoropolymers. In: Seymour RB, Kirshenbaum GS, editors. High performance polymers: Their origin and development. New York (NY): Elsevier. p 279–286.

Puts G, Crouse P, Ameduri B. 2014. Thermal degradation and pyrolysis of polytetrafluoroethylene. In: Smith DW, Iacano TS, Iyer SS, editors Handbook of fluoropolymer science and technology. New York (NY): Wiley. p 81–104.

Scheringer M, Trier X, Cousins IT, de Voogt P, Fletcher T, Wang, Z, Webster TF. 2014. Helsingor statement on poly- and perfluorinated alkyl substances (PFAS). *Chemosphere* 114:337–339.

Schlipf M, Schwalm T. 2014. Closing the recyling loop. *Kunststoffe Intl* 2014/06. [cited 2017 July 12]. https://www.kunststoffe.de/en/journal/archive/article/up-cycling-of-end-of-life-fluoroplastics-841786.html

[SPI] Society of the Plastics Industry. 2005. SPIs guide to safe handling of fluoropolymers. Washington (DC).

Starkweather Jr HW, Wu S. 1989. Molecular weight distribution in polymers of tetrafluoroethylene. *Polymer* 30:1669–1674.

Suwa T, Takehisa M, Machi S. 1973. Melting and crystallization behavior of poly(tetrafluoroethylene). New method for molecular weight measurement of poly(tetrafluoroethylene) using a differential scanning calorimeter. *J Appl Polym Sci* 17:3253–3257.

Taylor PH, 2009. ECA incineration testing program: Laboratory-scale incineration testing of fluoropolymers. Dayton (OH): USEPA. USEPA Docket No. OPPT-2003-0071.

Tuminello WH. 1989. Molecular weight distributions of tetrafluoroethylene-hexafluoropropylene copolymers. *Polym Eng Sci* 29:645–653.

Tuminello WH, Buck WH, Kerbow DL. 1993. Rheological molecular weight distribution determination of ethylene/ tetrafluoroethylene copolymers: Implications for long-chain branching. *Macromolecules* 26:499–503.

[UBA] Umweltbundesamt. 2017. Protecting the sources of our drinking water from mobile chemicals. A proposal for implementing criteria and an assessment procedure to identify persistent, mobile and toxic (PM or PMT) substances registered under REACH. Dessau-Roßlau (DE). [cited 2017 July 12]. https://www.umweltbundesamt.de/en/publikationen/protecting-the-sources-of-our-drinking-water-from

[UNEP] United Nations Environment Programme. 2001. Conference of Plenipotentiaries on the Stockholm Convention. UNEP/POPS/CONF/2. [cited 2017 July 12]. http://www.wipo.int/edocs/trtdocs/en/unep-pop/trt_unep_pop_2.pdf

[UNEP] United Nations Environment Programme. 2009: Decision SC-4/17. Geneva (CH). [cited 2017 July 12]. http://chm.pops.int/Portals/0/download.aspx?d=UNEP-POPS-COP.4-SC-4-17.English.pdf; also accessible from table of new POPs: http://www.pops.int/TheConvention/ThePOPs/TheNewPOPs/tabid/2511/Default.aspx

[UNEP] United Nations Environment Programme. 2011. UNEP-POPS-POPRC.11-POPRC-11-4.English.docx. Geneva (CH). [cited 2017 July 12]. http://www.pops.int/TheConvention/POPsReviewCommittee/Meetings/POPRC11/Overview/tabid/4558/mctl/ViewDetails/EventModID/871/EventID/553/xmid/13837/Default.aspx

[UNEP] United Nations Environment Programme. 2017a. Proposal for listing PFHxS (UNEP/POPS/POPRC.13/4). Geneva (CH). [cited 2017 July 12]. http://chm.pops.int/Convention/POPsReviewCommittee/Chemicals/tabid/243/Default.aspx

[UNEP] United Nations Environment Programme. 2017b. Risk management profile for PFOA, (UNEP/POPS/POPRC.13/7/Add.2). Geneva (CH). [cited 2017 July 12]. http://chm.pops.int/Convention/POPsReviewCommittee/Chemicals/tabid/243/Default.aspx

[USC] US Congress. 1976. The Toxic Substance Control Act. 15 U.S.C. 2601-2671. Public Law 94–469.

[USEPA] US Environmental Protection Agency. 1997a. Chemistry assistance manual for premanufacture notification submitters. Washington (DC). EPA 774-R-97-003. March 1997.

[USEPA] US Environmental Protection Agency. 1997b. Polymer exemption guidance manual. Washington (DC). EPA-744-B-97-001. June 1997.

[USEPA] US Environmental Protection Agency. 1999. Category for persistent, bioaccumulative, and toxic new chemical substances. *Fed Regis* 4(213). 1999 Nov 4.

[USEPA] US Environmental Protection Agency. 2010. Reviewing new chemicals under the Toxic Substances Control Act (TSCA) – EPA's Review Process - Chemical categories used to review new chemicals under TSCA: TSCA New Chemicals Program (NCP) Chemical Categories. Washington (DC): USEPA Office of Pollution Prevention and Toxics. [cited 2017 July 12]. http://www.epa.gov/oppt/newchems/pubs/npcchemicalcategories.pdf

[USEPA] US Environmental Protection Agency. 2012. Sustainable futures/P2 framework manual.

[USEPA] US Environmental Protection Agency. 2017a. US Environmental Protection Agency, PFOA Stewardship Program. Washington (DC). [cited 2017 July 12]. https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-management-and-polyfluoroalkyl-substances-pfass#tab-3

[USEPA] US Environmental Protection Agency. 2017b. Using predictive methods to assess hazard under TSCA. Washington (DC). [cited 2017 July 12]. https://www.epa.gov/tsca-screening-tools/using-predictive-methods-assess-hazard-under-tsca

[USFDA] US Food and Drug Administration. 2017. Guidance for industry: Preparation of premarket submissions for food contact substances: Chemistry recommendations. College Park (MD). [cited 2017 July 12]. https://www.fda.gov/Food/GuidanceRegulation/GuidanceDocuments RegulatoryInformation/ucm081818.htm#iid2

[USFDA] US Food and Drug Administration Center for Drug Safety and Radiological Health. 2016. Use of International Standard ISO 10993-1, "Biological evaluation of medical devices – Part 1: Evaluation and testing within a risk management process" Guidance for Industry and Food and Drug Administration Staff Document. Silver Spring (MD). [cited 2017 July 12]. https://www.fda.gov/ucm/groups/fdagov-public/@fdagov-meddev-gen/documents/document/ucm348890.pdf

[USFR] US Federal Register. 1984. Premanufacture Notification Exemptions for polymers; Final rule 49 FR 46066, 1984 Nov 21. FRL-2439-1.

[USFR] US Federal Register. 1995. Premanufacture notification exemptions; Revisions of exemptions for polymers; Final rule. *Fed Regist* 60(60): 16316–16336. Environmental Protection Agency. 60 FR 16316. 1995 Mar 29. FRL–4929–8.

[USFR] US Federal Register. 2006. Premanufacture notification exemption for polymers; Amendment of polymer exemption rule to exclude certain perfluorinated polymers. 40 CFR Part 723. 2006 Mar 7. Fed Reg No 06-02152.

[USFR] US Federal Register. 2010. Premanufacture notification exemption for polymers; Amendment of polymer exemption rule to exclude certain perfluorinated polymers. 40 CFR Part 723. 2010 Jan 27. EPA-HQ-OPPT-2002-0051; FRL-8805-5. RIN 2070-AD58.

[USFR] US Federal Register. 2012. Polymers (b). 40 CFR Sect 723.250.

[USFR] US Federal Register. 2016a. Indirect food additives. 21 CFR, Sect 174–178.

[USFR] US Federal Register. 2016b. Perfluorocarbon resins. 21 CFR, Sect 177.1550.

[USP] US Pharmacopeia 40. 2018. National Formulary 35 (USP), General Chapter 88, Biological Reactivity Tests, In Vivo.

[USP] US Pharmacopeial Convention. 2011. US Pharmacopeia National Formulary 2011: USP 34 NF 29. Rockville (MD). General Notices, Section 5.3.0, p 6.

Wagner PM, Nabholz JV, Kent RJ. 1995. The new chemicals process at the Environmental Protection Agency (EPA): Structure-activity relationships for hazard identification and risk assessment. *Toxicol Lett* 79:67–73.

Williams DF. 1987. Definitions in biomaterials. Amsterdam (NL): Elsevier. 72 p.

W.L. Gore. 2017. Fabrics goal for eliminating PFCs of environmental concern. [cited 2017 July 12]. https://www.gore-tex.com/pfcgoal

DOI: 10.1002/ieam.4035

PSR 1985 NOBEL PEACE PRIZE PHYSICIANS FOR SOCIAL RESPONSIBILITY
U.S. AFFILIATE OF INTERNATIONAL PHYSICIANS FOR THE PREVENTION OF NUCLEAR WAR

FRACKING WITH "FOREVER CHEMICALS" IN NEW MEXICO

Evidence Shows Oil and Gas Companies Have Used PFAS in New Mexico Wells; Water Risks Especially High for Groundwater-Dependent State

By Dusty Horwitt, J.D.
and Barbara Gottlieb

Data Analysis by Gary Allison

April 12, 2023

NMOGA Exhibit D4

CONTENTS

Cover photo: Williams Field Services Natural Gas Processing Facility, Bloomfield, New Mexico, Oct. 2012. Photo credit: Jane Pargiter, EcoFlight.

Maps by Matt Kelso, FracTracker Alliance

Graphic Design: twocatsgraphics.com

Physicians for Social Responsibility thanks the Rockefeller Family Fund for its generous support. We thank the following for their contributions to this report: Mario Atencio, Diné C.A.R.E.; Ally Beasley, Western Environmental Law Center; Linda Birnbaum Ph.D., D.A.B.T., A.T.S., former Director National Institute of Environmental Health Sciences; Soni Grant, Center for Biological Diversity; Norman Gaume, P.E. (ret.), retired water manager; Zacariah Hildenbrand Ph.D.; Kevin Schug Ph.D.; Kayley Shoup, Citizens Caring for the Future; Wilma Subra, Subra Company; Melissa Troutman, WildEarth Guardians.

EXECUTIVE SUMMARY

Previously unpublicized information unearthed by Physicians for Social Responsibility (PSR) shows that since at least 2013, oil and gas companies used in New Mexico's oil and gas wells a class of extremely toxic and persistent chemicals known as PFAS. However, gaps in New Mexico's disclosure rules prevent the public from knowing how widely PFAS – or other toxic chemicals – have been used. These findings raise concerns that New Mexicans may unknowingly be exposed to highly hazardous substances that are toxic in minuscule amounts.

PFAS are a class of chemicals known for their toxicity at extraordinarily low levels, their multiple negative health effects including cancer, and their persistence in the environment, leading to their nickname, "forever chemicals." Using these chemicals may be particularly risky in a state where 80 percent of the population depends on groundwater for drinking water. Oil and gas production and waste disposal operations can contaminate groundwater with toxic chemicals including PFAS – and, once contaminated, groundwater is particularly difficult to clean up.

The present report is based on data publicly disclosed by the oil and gas industry regarding the use of chemicals in the stage of oil and gas operations known as hydraulic fracturing, or fracking. We found that between 2013 and 2022, oil and gas companies injected more than 200 oil and gas wells in six counties, in both the Permian and San Juan Basins, with the PFAS known as PTFE (marketed as Teflon). Oil and gas companies also injected wells in Lea County in the Permian Basin with the PFAS called fluoroalkyl alcohol substituted polyethylene glycol.

However, the number of cases of PFAS use we have been able to definitively identify in New Mexico oil and gas extraction may significantly underrepresent the reality. That is in large part because New Mexico law allows oil and gas companies to withhold fracking chemical identities from the public and regulators by claiming them as "trade secrets."

Between 2013 and 2022, oil and gas companies disclosed their use of fracking chemicals in 9,066 oil and gas wells. Of those wells, the companies injected more than 8,200 (over 90 percent) with at least one trade secret chemical per well. Trade secret chemicals used over this period totaled more than 240 million pounds. Information about these chemicals was limited, but scientific experts told PSR that chemicals injected into two dozen wells in the Permian Basin were PFAS, may be PFAS, or are precursor chemicals that could degrade into PFAS. Oil and gas companies injected more than 3,600 of the 8,200 wells with surfactants that could be fluorosurfactants, a class of chemical that include multiple PFAS. Should only a fraction of the unidentified chemicals used in New Mexico's oil and gas wells be PFAS, they could pose a significant threat. (An interactive map showing the locations of wells injected with PFAS and trade secret chemicals is https://psr.org/new-mexico-pfas-map/ Users can zoom in to identify wells near them.)

By shielding from public view the chemicals injected into oil and gas wells, weak disclosure rules raise the potential that New Mexicans may be directly exposed, or their groundwater and well water may be exposed, to PFAS (and other toxic chemicals) from hundreds or even thousands of oil and gas wells and waste disposal sites.

In light of these findings, PSR recommends the following:

- **Halt PFAS use in oil and gas extraction.** New Mexico should follow the lead of Colorado, a major oil- and gas-producing state that in June 2022 passed legislation banning the use of PFAS in oil and gas wells. Furthermore, New Mexico and the U.S. Environmental Protection Agency (EPA) should prohibit PFAS from being used, manufactured, or imported for oil and gas extraction. Many PFAS are replaceable with less-persistent and less-toxic alternatives.
- **Expand public disclosure.** New Mexico should greatly expand its requirements for public disclosure of oil and gas chemicals. TThe state could again follow the example offered by Colorado by requiring disclosure of all individual chemicals used in oil and gas wells, without

exceptions for trade secrets, while still protecting chemical product formulas. New Mexico should also require disclosure on the part of chemical manufacturers and require chemical disclosure prior to permitting, as have California, West Virginia, and Wyoming.

- **Increase testing and tracking.** New Mexico and/or the U.S. EPA should determine where PFAS have been used in oil and gas operations in the state and where related wastes have been deposited. They should test nearby residents, water, soil, flora, and fauna for PFAS, both for the particular type(s) of PFAS used and for organic fluorine to detect the presence of other PFAS. and/or their breakdown products. Testing equipment should be used that is sensitive enough to detect PFAS at a level of single-digit parts per trillion or lower.

- **Require funding and cleanup**. Oil and gas and chemical firms should be required to fund environmental testing for PFAS in their areas of operation, and should PFAS be found, be required to fund cleanup. If water cleanup is impossible, companies responsible for the use of PFAS should pay for alternative sources of water for household and agricultural uses, as needed.

- **Remove New Mexico's oil and gas hazardous waste exemption.** New Mexico exempts oil and gas industry wastes from state hazardous waste rules. New Mexico should follow New York's lead and remove its state-level hazardous waste exemption for the oil and gas industry.

- **Reform New Mexico's regulations for oil and gas production wells and underground injection disposal wells.** The state should prohibit production wells and underground wastewater disposal wells close to underground sources of drinking water, homes, health care facilities and schools, require groundwater monitoring for contaminants near the wells, and for disposal wells, require full public disclosure of chemicals in the wastewater.

- **Transition to renewable energy and better regulation.** Given the use of highly toxic chemicals in oil and gas extraction, including but not limited to PFAS, as well as climate impacts of oil and gas extraction and use, New Mexico should transition away from oil and gas production and move toward renewable energy and efficiency while providing economic support for displaced oil and gas workers. As long as drilling and fracking continue, the state should better regulate these practices so that New Mexicans are not exposed to toxic substances and should empower local governments also to regulate the industry. When doubt exists as to the existence or danger of contamination, the rule of thumb should be, "First, do no harm."

Ruins at Chaco Culture National Historic Park, near Nageezi, New Mexico, Sept. 2009. Photo Credit: SkybirdForever, https://commons.wikimedia.org/wiki/File:Chaco_Canyon_-_Pueblo_Bonito_kiva_and_ruins.JPG.

CH. 1 PFAS: A MANMADE THREAT TO HEALTH AND THE ENVIRONMENT USED IN NEW MEXICO'S OIL AND GAS WELLS

a. PFAS Used in New Mexico Wells

Physicians for Social Responsibility (PSR) has identified evidence from publicly reported oil and gas industry records that a highly dangerous class of chemicals, known as per- and polyfluoroalkyl substances (PFAS), has been used in New Mexico's oil and gas* wells for hydraulic fracturing ("fracking"). PFAS are known for their toxicity at extremely low levels,[1] their multiple negative health effects including cancer,[2] and their persistence in the environment, which has endowed them with their nickname, "forever chemicals."[3] Fracking is the stage of oil and gas operations that typically involves high-pressure injections into oil and gas wells of up to tens of millions of gallons of water, sand, and chemicals to fracture rock formations and free up trapped oil and gas.[4]** It is possible that PFAS have been used in additional stages and methods of oil and gas production in New Mexico.

The likely use of PFAS in oil and gas production in New Mexico was first exposed in 2021, initially in a report by PSR[5] and subsequently by Public Employees for Environmental Responsibility.[6] Based on fracking chemical disclosures made to the state and to the nongovernmental organization FracFocus, PSR is now able to identify New Mexico oil and gas wells definitively known to have been injected with PFAS between 2013 and 2022. They include 227 wells in six counties that were injected with PTFE, also known as Teflon and identified by the U.S. Environmental Protection Agency (EPA) as a PFAS.[7] Another 34 wells in Lea county were injected with fluoroalkyl alcohol substituted polyethylene glycol, also identified as a PFAS by EPA.[8] (See chapter 2 for details on these chemicals.) In reaching definitive conclusions about these chemicals, PSR relied on Chemical Abstracts Service (CAS) numbers that are unique numeric identifiers assigned to chemicals by the American Chemical Society.[9] Scientists consider

---

* Gas, the principal component of which is methane, is also known as "natural" gas, "fossil" gas and "fracked" gas.

** In this report, the term "fracking" is used to discuss a particular stage in oil and/or gas production as distinct from other stages or methods of production such as drilling that precedes fracking. The terms "oil and gas production," "oil and gas extraction," and "oil and gas operations" cover the entire process of producing oil and/or gas.

Table 1. Disclosed Use in Fracking of PFAS and Possible PFAS in New Mexico Oil and Gas Wells, 2013-2022

Chemical Name	Chemical Abstracts Service (CAS) Number	PFAS or PFAS Precursor?	Source of Determination as PFAS or PFAS Precursor
PTFE/Teflon	9002-84-0	PFAS	Identified as PFAS on EPA's Master List of PFAS
Fluoroalkyl alcohol substituted polyethylene glycol	65545-80-4	PFAS	Identified as PFAS on EPA's Master List of PFAS
Nonionic fluorosurfactant	Unknown (identity withheld as a trade secret)	Could be PFAS or PFAS precursor.	Some chemical experts identify nonionic fluorosurfactants as PFAS or PFAS precursors, others as likely to be PFAS or possibly PFAS.
Trade secret surfactants	Unknown (identity withheld as a trade secret)	Could include fluorosurfactants that are PFAS or PFAS precursors.	No determination possible where chemical identity is withheld.
Trade secret chemicals	Unknown (identity withheld as a trade secret)	Could include PFAS or PFAS precursors.	No determination possible where chemical identity is withheld.

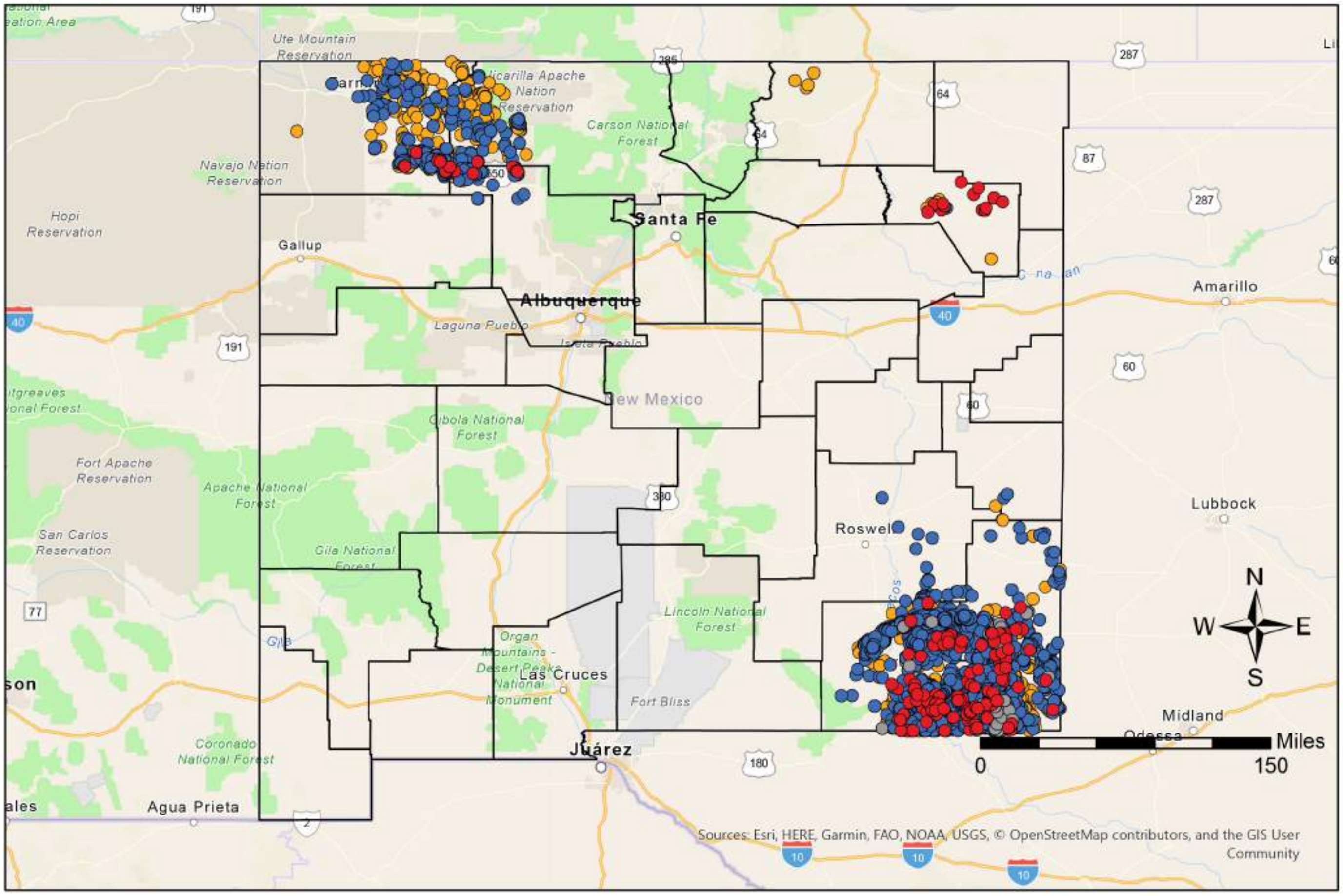
This table shows the types of chemicals that are PFAS or could be PFAS that oil and gas companies injected for fracking into oil and gas wells in New Mexico between January 1, 2013 and September 29, 2022. PFAS precursors are chemicals that can break down into PFAS. Some scientists believe that if a chemical can break down into a PFAS, it could or should be considered a PFAS.[12]

CAS numbers the best way to identify chemicals because chemicals can have multiple names or trade names but only one CAS number.[10]

In addition, PSR found that oil and gas companies injected 24 wells in Eddy and Lea Counties with unspecified nonionic fluorosurfactants that could be PFAS or precursors (chemicals that could degrade into PFAS), according to three chemists and a board-certified toxicologist who reviewed the fluorosurfactants' names.[11]

The wells injected with PFAS or possible PFAS may significantly underrepresent the extent of PFAS use in the state's oil and gas wells, due to gaps in chemical disclosure

New Mexico Oil & Gas Wells Fracked with PFAS and Possible PFAS, Including Trade Secret Chemicals, 2013-2022



Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

- ● Wells Fracked with Fluoroalkyl Alcohol Substituted Polyethylene Glycol (a PFAS), Fluorosurfactants (possibly PFAS)
- 🔴 Wells Fracked with PTFE/Teflon (a PFAS)
- 🔵 Wells Fracked with Trade Secret Surfactants (possibly PFAS)
- 🟠 Wells Fracked with Trade Secret Chemicals (possibly PFAS)
- ☐ Counties

This map shows the location of oil and gas wells in New Mexico known to have been fracked between January 1, 2013 and September 29, 2022 using PTFE/Teflon (a known PFAS), fluoroalkyl alcohol substituted polyethylene glycol (a known PFAS), fluorosurfactants that may be PFAS or PFAS precursors, trade secret chemicals, and/or trade secret surfactants. An interactive version of the map is available at https://psr.org/new-mexico-pfas-map/. Users can zoom in to identify wells near them. For a more detailed explanation of data sources, see the Appendix.

rules, including those that allow oil and gas companies to conceal from the public as trade secrets the specific identities of chemicals they use in fracking. **PSR's review of fracking chemical disclosure in New Mexico found that oil and gas companies disclosed that they used fracking chemicals between 2013 and 2022 in 9,066 oil and gas wells. Of those wells, the companies injected more than 90 percent with at least one trade secret chemical and more than 40 percent with at least one trade secret surfactant. Some of these trade secret chemicals could be PFAS.**

The use of these chemicals is particularly alarming as New Mexico's oil production has increased seven-fold in roughly a decade, from about 65.5 million barrels in 2010 to more than 457 million barrels in 2021,[13] and gas production has roughly doubled from about a trillion cubic feet in 2013 to more than two trillion cubic feet in 2021.[14] While these increases, driven largely by production in the Permian Basin,[15] mean more revenue for the state,[16] they also mean more wells being drilled and fractured, more greenhouse gas emissions,[17] and more opportunities for drilling companies to use PFAS or other toxic chemicals.

b. Manmade and Dangerous: PFAS's History and Health Effects

PFAS are a class of thousands of synthetic chemicals manufactured to have properties that are valuable in multiple industrial contexts, including being slippery, oil- and water-repellant, and able to serve as dispersants or foaming agents.[18] PFAS have been called "perfluorinated chemicals" and "polyfluorinated compounds," or PFCs, though the term currently preferred by EPA is PFAS.[19]

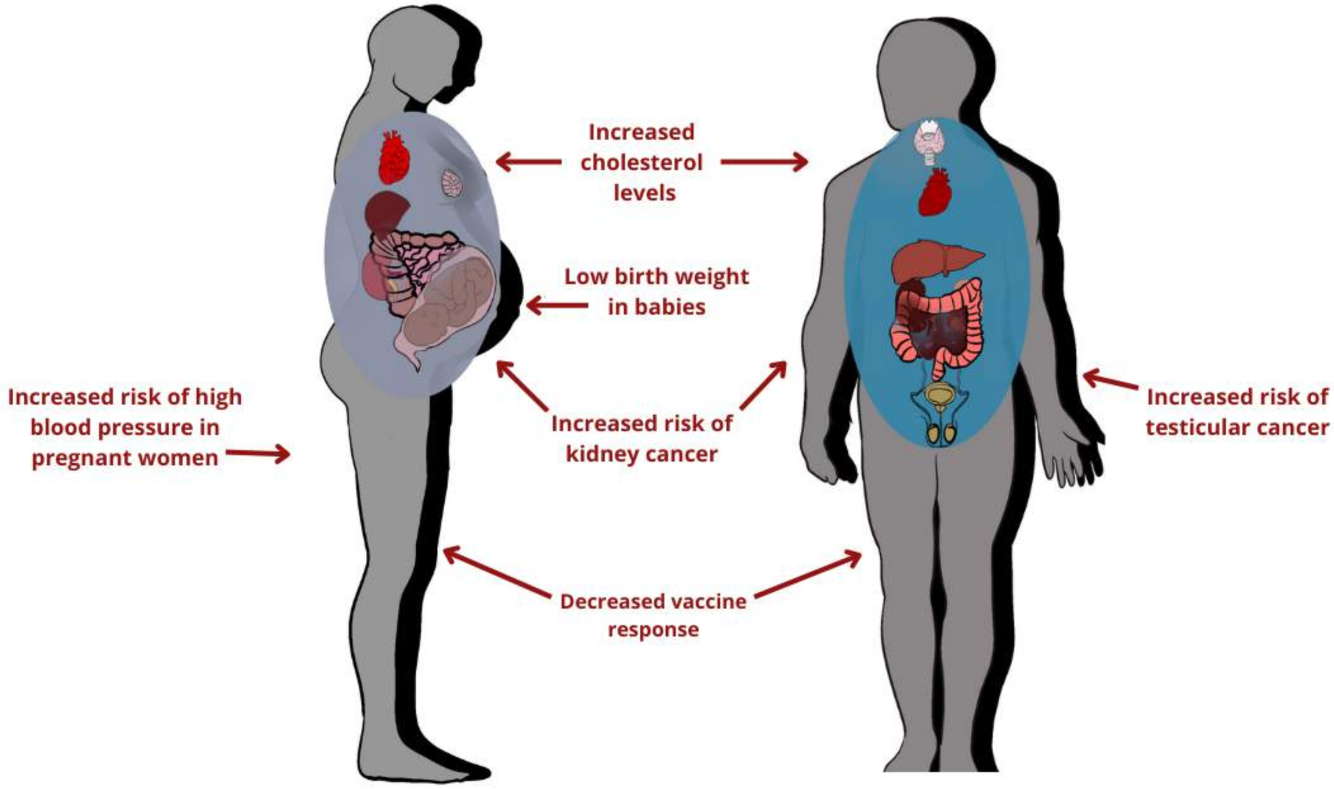
The first PFAS to be sold commercially was created by a chemist at Dupont and was patented as Teflon. Since 1949, it has been used in thousands of products, from nonstick cookware to waterproof clothing to plastics to dental floss.[20] Other PFAS chemicals, the most prominent of which are known as PFOA and PFOS, were used in food packaging, fire-fighting foam, and in 3M's widely used fabric protector, Scotchgard.[21] EPA reported in 2021 that about 650 types of PFAS remained in commerce.[22] Weak chemical disclosure laws make it difficult for the Agency to identify which PFAS chemicals are used, and where.

Between the 1960s and 1990s, researchers inside Dupont and 3M became aware that at least some of the PFAS they were manufacturing or using, particularly PFOA and PFOS, were associated with health problems including cancers and birth defects, had accumulated in people worldwide, and persisted in the environment.[23]

Many of these facts, kept internal by the companies, came to light after attorney Rob Bilott filed lawsuits in 1999 and 2001 accusing Dupont of causing pollution in and around Parkersburg, West Virginia with PFOA, a type of PFAS then used in making PTFE (Teflon).[24] In December 2011, as part of Dupont's settlement of the 2001 lawsuit, a team of epidemiologists completed a study of the blood of 70,000 West Virginians and found a probable link between PFOA and kidney cancer, testicular cancer, thyroid disease (over- or under-production of hormones by the thyroid gland), high cholesterol, pre-eclampsia (a potentially dangerous complication during pregnancy characterized by high blood pressure and signs of damage to other organ systems, most often the liver and kidneys), and ulcerative colitis (a disease causing inflammation and ulcers in the large intestine or colon).[25]

Current peer-reviewed scientific research on PFAS suggests that exposure to certain levels of some PFAS may lead to adverse health outcomes. Research findings differ, as different studies have examined different PFAS chemicals, different types or levels of exposure, or different exposed populations. However, some findings are more widely endorsed; for example, the U.S. Environmental Protection Agency (EPA)[26] and the Center for Disease Control and Prevention's Agency for Toxic Substances and Disease Registry (ATSDR)[27] agree that exposure to high levels of certain PFAS may lead to increased risk of high blood pressure in pregnant women; low birth weight in babies;

POTENTIAL HEALTH EFFECTS OF PFAS EXPOSURE



Exposure to PFAS chemicals can result in a variety of serious health effects including those indicated above.Source: U.S. Environmental Protection Agency, Agency for Toxic Substances and Disease Registry. Graphic by Astra Robles

increased risk of kidney or testicular cancer; decreased vaccine response, and increased cholesterol levels. Research is ongoing to determine the health effects of different levels of exposure to different PFAS, including the health effects of long-term, low-level PFAS exposure, especially in children. **See graphic above.**

PFAS are not only highly toxic; they also demonstrate extreme persistence in the environment. PFAS' nickname "forever chemicals" reflects their chemistry – created by chemical manufacturers – that features a bond between fluorine and carbon atoms that is among the strongest in chemistry and rarely if ever exists in nature. The result: chemicals that are extremely resistant to breaking down.[28] PFAS are also extremely mobile in water,[29] making them able to spread through the environment via groundwater or surface water. Another risk, discussed in Chapter 5, is that PFAS could compound the health effects from other dangerous chemicals associated with oil and gas production.

c. EPA Recognizes Risks of PFAS

EPA has been slow to regulate PFAS, but the agency has taken actions, particularly in recent years, that recognize

PFAS's extraordinary risks. In June 2022, reflecting growing public concern about PFAS, EPA significantly lowered its non-binding health advisory level for PFOA and PFOS in drinking water. Previously, EPA had set the combined health advisory level for these chemicals at 70 parts per trillion.[30] "**The new published peer-reviewed data and draft EPA analyses…" EPA wrote in June 2022, "indicate that the levels at which negative health outcomes could occur are much lower than previously understood.**"[31] EPA set its new interim health advisory level for PFOA in drinking water to 0.004 parts per trillion and its interim health advisory level for PFOS to 0.02 parts per trillion.[32] EPA also set new final health advisory levels for two other PFAS known as GenX and PFBS at 10 parts per trillion and 2,000 parts per trillion, respectively.[33] EPA said that its interim health advisory levels were intended to provide guidance until enforceable drinking water regulations for PFAS take effect.[34]

EPA then in March 2023 released proposed standards for levels of six PFAS in drinking water. These included a level of four parts per trillion for both PFOA and PFOS. EPA explained in an email, sent in response to a question from PSR, the difference between the health advisory levels and the proposed drinking water standards:

> Health advisories reflect EPA's assessment of health risks of a contaminant based on the best available science and provide advice and information on actions that water systems may take to address contamination for these and other PFAS.[35]

Besides focusing on possible health effects, health advisories differ from rules in that they do not take into account whether a particular level of protection can be achieved or at what cost.[36] In this respect they resemble EPA's proposed Maximum Contaminant Level Goal, which for PFOA and PFOS is zero in drinking water.

EPA's interim health advisory levels mean that the toxicity of PFOA is almost beyond comprehension. According to EPA's advisory levels, one tablespoon of PFOA would be enough to contaminate 1.75 trillion gallons of water,[37] which is more than twice the total storage capacity of Elephant Butte Reservoir (720 billion gallons),[38] which forms New Mexico's largest lake on the Rio Grande River in the southwestern part of the state.[39] (Current levels in the lake are far below total storage capacity due to drought.[40]) EPA's new health advisory levels further show that PFOS is similarly extraordinarily toxic. In March 2023, EPA proposed drinking water regulations that would limit the amount of PFOA and PFOS in drinking water to four parts per trillion. The agency also proposed that drinking water providers limit the combined levels of four other types of PFAS: PFNA, PFHxS, PFBS, and/or GenX Chemicals. The agency said that it expects to finalize the rule by the end of 2023.[41]

Several experts told PSR that because of the extreme potency of certain types of PFAS and the fact that chemical makers have created thousands of these forever chemicals, they would recommend particular testing methods to detect PFAS in the environment. The scientists are Linda Birnbaum, Ph.D., D.A.B.T., A.T.S., a board-certified toxicologist and former director of the National Institute of Environmental Health Sciences;[42] Zacariah Hildenbrand Ph.D., research professor in Chemistry and Biochemistry at the University of Texas at El Paso;[43] Kevin Schug Ph.D., Shimadzu Distinguished Professor of Analytical Chemistry at the University of Texas at Arlington,[44] and Wilma Subra, holder of a master's degree in chemistry and recipient of a John D. and Catherine T. MacArthur Foundation "Genius" grant for her work helping to protect communities from toxic pollution.[45] All were in agreement in recommending the use of testing equipment that can detect PFAS in concentrations at least as low as single-digit parts per trillion. They further recommended testing for total organic fluorine in addition to testing for specific types of PFAS. Total organic fluorine is a marker that would indicate the presence of PFAS even if a specific PFAS were not tested for. Testing for specific PFAS only might fail to detect other forms of PFAS present in the sample.

d. PFAS Already Present in New Mexico's Environment

Evidence has mounted over the years of cases of PFAS pollution from a variety of sources, including in New Mexico.

In 2018, the U.S. Air Force reported that PFAS had been detected in groundwater below Cannon Air Force base in Clovis and beneath Holloman Air Force base outside Alamogordo.[46]

At Cannon Air Force base, the levels were as high as 26,200 parts per trillion in groundwater for combined PFOA and PFOS.[47] At Holloman Air Force base, the levels reached as high as 1,294,000 parts per trillion for combined PFOA and PFOS.[48] (As noted above, EPA's health advisory levels for PFOA and PFOS in drinking water are 0.004 parts per trillion and 0.02 parts per trillion, respectively.) In both cases, the pollution was linked to the use of firefighting foam that contained PFAS.[49] It is unclear whether both PFOA and PFOS were in the foam. The Interstate Technology Regulatory Council reports that firefighting foam used between the 1960s and 2002 can contain both types of PFAS as well as precursors that may degrade into PFOA.[50] The pollution near Cannon Air Force Base devastated a local dairy farm. Because of the pollution, farmer Art Schaap told the Albuquerque Journal in 2022 that since he learned of the PFAS contamination in his water in 2018, he had been unable to sell his cow's milk or meat. He was forced to euthanize thousands of cows, and he and the state must determine how to safely dispose of the PFAS-tainted carcasses so that the persistent pollutants do not cause further contamination. "I've lost so much money, I don't know if I can restart," Schaap told the Journal.[51]

The state Environment Department began a water sampling effort in mid-2020 with support from the U.S. Geological Survey to determine levels of PFAS around the state, and the concentrations discovered showed some cause for concern.[52] The sampling, which ran from August 2020 to November 2021, focused on ground and surface water supplies in 19 New Mexico counties.[53] In a news release published in January 2021, the Department reported that "To date, the data from this effort does not indicate any imminent public health threats….None of the results received so far show levels of PFOS or PFOA at or above the [EPA's] Lifetime Health Advisory." However, that health advisory of 70 parts per trillion of combined PFOA and PFOS is now outdated. Under EPA's June 2022 interim health advisory levels for PFOA and PFOS, multiple samples of water in New Mexico's sampling for PFAS have levels that are now judged unsafe. They range from 145 times to 9,000 times EPA's interim health advisory levels for PFOA and PFOS, including:

- 2.9 parts per trillion of PFOS in the Melrose water system in Curry County (145 times EPA's interim health advisory level);
- 8 parts per trillion of PFOA in the Alamogordo Domestic Water System/Golf Course Well in Otero County (2,000 times EPA's interim health advisory level), and
- 36 parts per trillion of PFOA in spring 10 of the Cloudcroft Water System in Otero County (9,000 times EPA's interim health advisory level).

"If, during the study, levels of PFOS and PFOA are detected in drinking water resources above the Lifetime Health Advisory," the department wrote, "NMED will work with public water systems to identify the best mitigation options, if requested." It is unclear if the department will take the same steps if the levels detected are above EPA's much more protective interim health advisory levels. The department has said on a separate website that "PFAS contamination in New Mexico is one of the New Mexico Environment Department's top priorities, as is the protection of human health and the environment."[54] The Department added that in the absence of federal drinking water standards for PFAS, it was considering developing standards of its own.[55]

e. Oil and Gas Operations Provide Many Potential Routes of Exposure to PFAS

Oil and gas operations in New Mexico deserve scrutiny as a possible additional source of PFAS contamination due to the now-documented use of PFAS in the state's oil and gas wells and the potential that people could be exposed to PFAS via multiple pathways.

An oil and/or gas site in Aztec, New Mexico, Sept. 2008. Photo credit: Jane Pargiter, EcoFlight.

EPA in its 2016 national report on fracking and drinking water found that fracking-related pollution could follow a number of pathways that could impact surface- and groundwater. The agency cited the following possible pathways to exposure:

- spills of fracking fluid that seep into groundwater;
- injection of fracking fluid into wells with cracks in the casing or cement, allowing the fluid to migrate into aquifers;
- injection of fracking fluids directly into groundwater;
- underground migration of fracking fluids through fracking-related or natural fractures;
- intersection of fracking fluid with nearby oil and gas wells,
- spills of wastewater after the fracking process is completed, and
- inadequate treatment and discharge of fracking wastewater to surface water supplies.[56]

PFAS used in oil and gas extraction could pollute water through any of these pathways, plus other routes discussed in more detail in Chapter 5 including through airborne releases and disposal of oil and gas wastewater in underground injection wells, a pathway that EPA did not examine in its 2016 report.[57]

PFAS contamination could further reduce available water supplies. EPA reported in 2013 that "about 87 percent of New Mexico's public water supply comes from groundwater. No other southwestern state gets such a large percentage of its domestic water from groundwater sources."[58] A representative of the federal Bureau of Reclamation told the Carlsbad Current-Argus in 2021 that in the Pecos River Basin in southeastern New Mexico, 80 percent of water was consumed by agricultural interests for irrigation, and 64 percent of that water came from groundwater. Much of the Pecos Basin overlaps with the heavily drilled Permian Basin.[59] The EPA stated in 2015 that "because groundwater usually moves slowly, contaminants generally undergo less dilution than when in surface water."[60] The agency added that

> [b]ecause ground water generally moves slowly, contamination often remains undetected for long periods of time. This makes cleanup of a contaminated water supply difficult, if not impossible. If a cleanup is undertaken, it can cost thousands to millions of dollars.[61]

Furthermore, water supplies are expected to shrink in future years as the climate heats up, making clean water supplies even more important. The Bureau of Reclamation forecast that in coming years, farmers in the basin will encounter higher temperatures and scarcer water.[62] PFAS contaminate could further reduce available water supplies.

f. PFAS: Among Many Dangerous Chemicals Used in Fracking

When used in oil and gas operations, PFAS may add to the cumulative human exposure to a host of toxic substances. In the fracturing stage of oil and gas production, chemicals serve a variety of purposes including killing bacteria inside the wellbore, reducing friction during high-pressure fracking, and thickening the fluid so that the sand, suspended in the gelled fluid, can travel farther into underground formations.[63] In its 2016 study of fracking and drinking water, the EPA identified 1,606 chemicals used in fracking fluid and/or found in fracking wastewater. While the agency found high-quality information on health effects for only about 10 percent (173) of these chemicals, that information was troubling. EPA found that health effects associated with chronic oral exposure to these chemicals include carcinogenicity, neurotoxicity, immune system effects, changes in body weight, changes in blood chemistry, liver and kidney toxicity, and reproductive and developmental toxicity.[64]

Chemicals used in the drilling stage that precedes actual fracturing can also pose health risks, including developmental toxicity and the formation of tumors, according to EPA regulators.[65] A disclosure form filed with the state of Ohio, one of only two states to require public disclosure of drilling chemicals (Colorado is the other),[66] shows that Statoil, Norway's state oil company (since renamed Equinor), has used the neurotoxic chemical xylene in drilling.[67] In short, when chemicals used in drilling, fracking or other stages and methods of oil and gas operations come into contact with people or the environment, they can produce serious negative health effects.[68]

CH. 2 PFAS USED IN NEW MEXICO'S OIL AND GAS WELLS: A DEEPER LOOK

a. PTFE (Teflon), a PFAS Fluoropolymer

One of the types of PFAS used for fracking in New Mexico's oil and gas wells between 2013 and 2022 was PTFE, commonly known as Teflon.

PTFE is a fluoropolymer, a type of plastic.[69] Scientists'[70] and environmentalists'[71] major concerns about PTFE and other fluoropolymers are related less to these substances themselves, but rather to the associated impacts of their production, use, and disposal. The production of PTFE and other fluoropolymers relies on the use of other, highly toxic PFAS that are used as production aids. As noted in a peer-reviewed study published in 2020, these other PFAS have included fluorosurfactants such as PFOA, whose risks are discussed in the previous chapter, and GenX, which is similarly harmful and has replaced PFOA in fluoropolymer production.[72] PTFE and other fluoropolymers may contain these more toxic PFAS fragments, and those fragments may leach out of the PTFE during use.[73] The authors of the 2020 paper noted that

> The levels of leachables…in individual fluoropolymer substances and products depend on the production process and subsequent treatment processes; a comprehensive global overview is currently lacking.[74]

In addition, PTFE may generate other PFAS if the PTFE breaks down under heat.[75]

The 2020 paper authors noted that the persistence in the environment of PTFE and other fluoropolymers could pose problems during disposal, observing that "Landfilling of fluoropolymers leads to contamination of leachates with PFAS and can contribute to release of plastics and microplastics.[76] One of the authors added in an email to PSR that if PTFE were used in oil and gas wells that have especially high temperatures, defined in publications by oilfield services company, Schlumberger, as 300º-350º F or higher for so-called "high-pressure, high-temperature wells,"[77] the PTFE could undergo a process called "thermolysis" and generate toxic PFAS called perfluoroalkyl carboxylic acids (PFCAs). As a result, he wrote, "there could be some additional problems that need some investigation."[78] A representative from New Mexico's Oil Conservation Division said that wells with the characteristics described by Schlumberger "would be atypical for any oil or gas producing wells in New Mexico." He added that the Oil Conservation Division does not track pressures or temperatures inside oil and gas wells, though operators sometimes report downhole pressures during initial production testing or "may report the temperatures in the well logs."[79] These data are publicly accessible online.[80]

In 2021, a coalition of national environmental organizations including the Center for Environmental Health, Clean Water Action, Ecology Center, Environmental Working Group, Natural Resources Defense Council, Safer States, and the Sierra Club voiced several environmental and health concerns regarding the risks of fluoropolymers such as

Table 2. Disclosed Use in Fracking of PTFE in New Mexico Oil and Gas Wells, 2013-2022

County Name	Number of wells injected with PTFE	Mass of PTFE (lbs.)[84]
Eddy	113	2028
Harding	14	2
Lea	74	557
Rio Arriba	2	2
San Juan	18)	10
Sandoval	6	6
Total	**227**	**2605**

This table shows by county the number of New Mexico wells in which oil and gas companies injected PTFE for fracking between 2013 and 2022. For a more detailed explanation of data sources, see the Appendix.

PTFE, based on their review of multiple scientific articles. The groups also noted that fluoropolymers are manufactured with chemicals that have an outsized negative effect on climate change.[81]

Public records make it difficult to know for what purpose PTFE was used. In most cases, either no purpose or various purposes were listed for chemical products, but the individual chemical components of these products were listed in a separate portion of the disclosure form, making it impossible to know which components are part of which product.[82] However, PTFE, which is marketed as Teflon, is known for its slipperiness, suggesting it might have been used as a friction reducer, a common purpose for fracking chemicals.[83]

Oil and gas companies that have disclosed using PTFE for fracking in New Mexico (Table 3) include ExxonMobil Corp., the nation's largest publicly traded oil and gas company;[85] and Devon Energy Corp.[86] and Occidental Petroleum Corp.,[87] both major producers in the Permian Basin.

Disclosure gaps in New Mexico law, discussed below, may prevent scientists and the public from knowing the extent of the use of PTFE and other PFAS in the state's oil and gas operations.

b. Fluoroalkyl Alcohol Substituted Polyethylene Glycol

The other type of PFAS disclosed as being used for fracking in New Mexico's oil and gas wells between 2013 and 2022 was fluoroalkyl alcohol substituted polyethylene glycol. EOG Resources, a major oil producer in the Permian and San Juan Basins,[88] injected 34 wells, all in Lea County, with a total of 6,400 pounds of this chemical. Fluoroalkyl alcohol

Table 3. Oil and Gas Companies that Fracked Wells in New Mexico Using PTFE, 2013-2022

Well Operator	Number of wells injected with PTFE	Total mass of PTFE (lbs.)
Devon Energy Production Company L. P.	60	456
Occidental Oil and Gas	45	354
Matador Production Company	23	204
Yates Petroleum Co.	22	No data available
Cimarex Energy Co.	13	134
Encana Oil & Gas Inc.	12	20
Whiting Petroleum	10	1
WPX Energy	9	No data available
XTO Energy/ExxonMobil	7	1286
BreitBurn Operating LP	6	2
ConocoPhillips Company/Burlington Resources	4	30
Energen Resources Corp.	3	No data available
COG Operating LLC	2	10
Dugan Production Corp.	2	No data available
Kaiser-Francis Oil Company	2	No data available
BOPCO, L.P.	1	No data available
DGP Energy	1	14
Mewbourne Oil Co.	1	No data available
Murchison Oil and Gas Co.	1	7
Oxy USA Inc.	1	No data available
Tap Rock Resources	1	90
V-F Petroleum Inc.	1	No data available

This table shows the oil and gas companies that fracked oil and gas wells in New Mexico with PTFE between 2013 and 2022. For a more detailed explanation of data sources, see the Appendix.

D4.14

substituted polyethylene glycol is listed on EPA's Master List of PFAS Substances under a different name.[89] PSR was able to identify it there using its CAS number of 65545-80-4, which appears in the FracFocus records.[90] Its purpose as declared in FracFocus is "oil field surfactant," suggesting that it could be a fluorosurfactant,[91] a type of chemical discussed in more detail in Chapter 3.

Limited toxicological data is available about chemical 65545-80-4, but according to data on the website of the National Library of Medicine's ChemIDplus, at high doses, the chemical is associated with convulsions or effects on the threshold for seizures; dyspnea, or shortness of breath; and muscle weakness.[92] A safety data sheet for the chemical published by its manufacturer says little about human health effects. "To the best of our knowledge," the safety data sheet says, referencing the substance using a trade name Zonyl® FSO-100, "the chemical, physical, and toxicological properties have not been thoroughly investigated."

Regarding impacts to the environment, the safety data sheet says, "Toxic to aquatic life with long lasting effects… Avoid release to the environment…Collect spillage…Dispose of contents/ container to an approved waste disposal plant."[93] A message on the website of ChemPoint, a chemical distributor, suggests that this chemical was phased out due to concerns that it could break down into PFOA or PFOS. A message apparently from Chemours, a company spun off from Dupont, says

> Zonyl® fluorosurfactant and repellent grades were discontinued between 2009 and 2014. Capstone® fluorosurfactants [a new type of fluorosurfactant] and repellents were introduced as sustainable replacements that meet the goals of the U.S. EPA 2010/15 PFOA Stewardship Program. They are based on short-chain molecules that cannot break down to PFOA or PFOS in the environment."[94]

However, as is discussed below, scientists have raised concerns about the health and environmental effects of these replacement chemicals.

Table 4. Disclosed Use of Fluoroalkyl Alcohol Substituted Polyethylene Glycol in New Mexico Oil and Gas Wells, 2013-2022

Well Operator	Number of wells injected with fluoroalkyl alcohol substituted polyethylene glycol – all in Lea County	Total weight of fluoroalkyl alcohol substituted polyethylene glycol (lbs.)
EOG Resources, Inc.	34	6,400

This table shows that EOG Resources, Inc., fracked oil and gas wells in New Mexico with fluoroalkyl alcohol substituted polyethylene glycol between 2013 and 2022. For a more detailed explanation of data sources, see the Appendix.

CH. 3

NEW MEXICO’S CHEMICAL DISCLOSURE LAWS SHIELD CHEMICAL IDENTITIES

a. New Mexico’s “Trade Secret” Law Shields Potentially Dangerous Substances, Including PFAS

The danger of exposure to unknown chemicals – PFAS and others – from oil and gas operations persists in New Mexico, despite state rules that generally require public disclosure of fracking and drilling chemicals.[95] On the face of it, these disclosure requirements seem effective. However, an important exception allows companies to avoid full and meaningful disclosure: The law allows chemical manufacturers, well operators and other companies in the chemical supply chain to withhold exact fracking and drilling fluid ingredient information if they deem it a trade secret.** [96] In some cases in New Mexico fracking chemical disclosure records, oil and gas operators disclose generic names of chemicals while withholding as trade secrets their specific identities. These generic identifiers include “nonionic fluorosurfactant,”[97] a chemical identified as PFAS or possible PFAS by several scientists as discussed below, and “proprietary Acid Inhibitor/Surfactant.”[98] Regrettably, the use of such vague descriptors can hide from public view the true identities of dangerous chemicals, including PFAS. The use of trade secrets to conceal chemicals’ specific identities effectively undermines the public health benefits of disclosure by preventing health professionals, first responders, state regulators and the public from knowing where PFAS – or other toxic chemicals – have been used in oil and gas wells.

In addition to allowing trade secret exemptions, New Mexico does not require public disclosure of chemicals used in drilling, enhanced oil recovery, or in other extraction techniques that are distinct from fracking per se. Chemicals used during the first stage of the drilling process would be highly likely to leach into groundwater since during this stage, according to EPA, drilling passes directly through groundwater zones[99] before any casing or cement is placed in the well to seal it off. The resulting potential for groundwater contamination makes public disclosure of chemicals used in drilling especially important, as these regulatory gaps increase the potential that New Mexicans could unknowingly be exposed to PFAS and other chemicals used during oil and gas extraction.[100]

In at least some cases, the New Mexico Oil Conservation Division has prohibited oil and gas companies from using “oil base muds” for drilling “until fresh water zones are cased and cemented providing isolation from the oil or diesel. This includes synthetic oils.”[101] Such “muds,” according to oilfield services company Schlumberger, are “generally synonymous with drilling fluid.”[102] According to the Oklahoma State University Extension Service, oil-based muds can include diesel fuel and the highly dangerous chemicals benzene, toluene, ethylbenzene, and xylene.[103]

It is unclear whether New Mexico’s prohibition would prohibit the use of PFAS during drilling that passes through fresh water zones.

b. Extensive Use of “Trade Secret” Claims Veils Actual Use

PSR found extensive application of the trade secret provisions under New Mexico’s fracking chemical disclosure rules – so extensive that it could serve to mask widespread use of PFAS in the state’s oil and gas wells. Our data analysis revealed that, between 2013 and 2022, New Mexico’s well operators claimed at least one fracking chemical as a trade secret in 8,293 oil and gas wells located across 11 counties. The trade secret chemicals used in New Mexico over this roughly 10-year period totaled 243 million pounds (see Table 5).[104] If even a small fraction of this weight were PFAS, that fraction could pose significant risks to health and the environment. In an effort to identify PFAS among these trade secret chemicals, PSR examined whether any were listed as a surfactant or a fluorosurfactant. According to EPA, surfactants are commonly used in fracking[105] and lower the surface tension of a liquid, the interaction at the surface between two liquids (called interfacial tension), or

---

** Trade secret information is also called “proprietary” or “confidential business information” (CBI).

the interaction between a liquid and a solid.[106] Compared to other surfactants, fluorosurfactants are said to be "superior in their aqueous surface tension reduction at very low concentrations and are useful as wetting and leveling agents, emulsifiers, foaming agents, or dispersants."[107] At least some fluorosurfactants are PFAS, including the dangerous chemicals PFOA and PFOS[108] and 8:2 fluorotelomer alcohol,[109] a nonionic fluorosurfactant[110] that can break down into PFOA.[111] Two scientists told PSR that all or most fluorosurfactants could be classified as a PFAS[112] while two other scientists were uncertain.[113]

Like the broader class of surfactants, fluorosurfactants are also used in fracking, and perhaps other stages and methods of oil and gas extraction, according to scientific and industry sources. In 2020, several scientists published an article in *Environmental Science: Processes and Impacts* showing that since 1956, PFAS including fluorosurfactants had been used or proposed to be used globally in oil and gas extraction techniques including chemical-driven gas production, chemical flooding, fracking, and the drilling that precedes fracking and other oil and gas production techniques.[114] In 2008, two authors, one of whom was identified as an employee at DuPont, wrote in the peer-reviewed *Open Petroleum Engineering Journal* that the use of fluorosurfactants was relatively common in the oil and gas industry and that their use was about to surge. They referred to fluorosurfactants as an "emerging technology" and stated,

> While fluorosurfactants have been used in gas and oil exploration for four decades, the increased demand for petroleum and the greater understanding of the benefits of fluorosurfactants have led to growing acceptance for fluorosurfactants throughout the petroleum industry.[115]

The authors did not explicitly say that fluorosurfactants used in oil and gas operations were PFAS but they described the fluorosurfactants in ways that are commonly used to describe PFAS. They wrote that "The use of fluorosurfactants is a recent but growing trend due to (i) the exceptional hydrophobic [water-repellent] and oleophobic [oil-repellent] nature of the perfluoroalkyl and perfluoroalkyl ether groups...The bond strength of the carbon-fluorine bond in perfluoroalkyl and perfluoroalkyl ether groups has been demonstrated as the key to remarkable overall stability for fluorochemicals and fluoropolymers."[116] This evidence suggests that any time an unidentified surfactant or fluorosurfactant is used in oil and gas production, there is a potential that it is a PFAS.

We found thousands of cases of oil and gas companies using at least one trade secret chemical that they described as a surfactant. These occurred in 3,680 wells, spread across 10 counties (see Table 5).[117] Operators' names for these chemicals were vague, including "surfactant" and "surfactant blend." These trade secret surfactants totaled 19.3 million pounds. (See examples from individual wells in Table 8 below.) While we cannot know what these trade secret chemicals are, should even a small percentage of them be fluorosurfactants that are PFAS, they could pose significant threats to human health and the environment.

In 24 wells (16 in Eddy County and 8 in Lea County), oil and gas companies disclosed the use of trade secret chemicals listed with the nonspecific name "nonionic fluorosurfactant" that are apparently fluorosurfactants and may be PFAS. The weight of these chemicals totaled 970 pounds.[118] Even if some of that volume were PFAS, it could pose significant health and environmental risks, depending on the chemicals' toxicity. According to two Texas university-based chemists, Hildenbrand and Schug, both of whom are authors of multiple peer-reviewed articles about chemicals related to oil and gas production,[119] nonionic fluorosurfactants are PFAS or could degrade into PFAS. In addition, Subra, the chemist and MacArthur Foundation "Genius" grant winner, identified the chemicals as potential PFAS.[120] Still another expert, toxicologist Birnbaum, informed PSR that the chemicals are likely to be PFAS.[121] Birnbaum added that PFAS, perhaps including the nonionic fluorosurfactants used in New Mexico's oil and gas wells, could degrade into one or more smaller PFAS[122] (Hildenbrand agreed). Birnbaum,[123] Hildenbrand,[124] Subra,[125] and Schug[126] generally agree that if a chemical can break down into a PFAS, it could or should be considered a PFAS.

PSR has had to rely on scientists to identify these chemicals as PFAS, potential PFAS, or PFAS precursors because the oil and gas companies that made the public disclosures to FracFocus withheld as trade secrets the chemicals' CAS numbers, data that would have enabled a precise identification of the chemicals. The identification in the FracFocus records included only the generic name "nonionic fluorosurfactant" and the trade name "S-222" for the product containing the nonionic fluorosurfactants,[127] information insufficient to identify the chemicals with specificity. The fact that only one trade name was listed each time the chemical was reported suggests that the fluorosurfactant might be the same chemical in each use, but it is impossible to know without a CAS number. The sole purpose for which these chemicals were listed: "Surfactants."[128] The locations of the wells where nonionic fluorosurfactants were used are displayed in the map on page two.

Table 5. Disclosed Use of Trade Secret Chemicals in New Mexico Oil and Gas Wells, 2013-2022

County Name	No. of wells injected with at least one trade secret chemical	Mass of all trade secret chemicals (lbs.)	No. of wells injected with trade secret surfactants	Mass of trade secret surfactants (lbs.)	No. of wells injected with nonionic fluoro-surfactants	Mass of nonionic fluoro-surfactants (lbs.)
Chaves	62	2,590,000	41	174,000	0	0
Colfax	4	615	0	0	0	0
De Baca	1	1,490	1	273	0	0
Eddy	3,787	110,000,000	1,895	9,120,000	8	106
Harding	15	2,820	3	33	0	0
Lea	3,606	120,000,000	1,435	8,270,000	16	860
McKinley	2	397	2	11	0	0
Rio Arriba	271	1,980,000	68	138,000	0	0
Roosevelt	5	15,000	2	12,300	0	0
San Juan	415	5,200,000	179	1,140,000	0	0
Sandoval	125	2,590,000	55	415,000	0	0
Total	**8,293**	**243,000,000**	**3,681**	**19,300,000**	**24**	**966**

This table shows by county the number of New Mexico wells in which oil and gas companies injected at least one trade secret fracking chemical, at least one trade secret surfactant, and/or at least one unspecified nonionic fluorosurfactant. It also shows the total combined weight of these chemicals by county and statewide. The total weight figures reflect the sum of all records for which we have enough information to calculate a chemical's weight. However, the total weight figures represent an undercount because many fracking chemical disclosures lack sufficient data to perform this calculation. The wells injected with trade secret surfactants are a subset of the wells injected with trade secret chemicals. The wells injected with unspecified nonionic fluorosurfactants are a subset of the wells injected with trade secret chemicals and trade secret surfactants. For a more detailed explanation of data sources, see the Appendix.

Data show that multiple oil and gas companies have injected oil and gas wells in New Mexico with trade secret chemicals that could be or could break down into PFAS. The excerpted table below shows the 15 companies that fracked the most wells in New Mexico between 2013 and 2022 with at least one trade secret chemical.

Table 6. Excerpt (full table in Appendix). Oil and Gas Companies that Fracked the Most Wells in New Mexico Using Trade Secret Chemicals and Trade Secret Surfactants, 2013-2022

Operator	Number of wells injected with trade secret chemicals	Number of wells injected with trade secret surfactants
EOG Resources, Inc.	1177	214
COG Operating LLC	844	438
Devon Energy Production Company L. P.	586	358
Mewbourne Oil Company	575	116
Occidental Oil and Gas	498	141
XTO Energy/ExxonMobil	442	203
Apache Corporation	439	386
Cimarex Energy Co.	336	186
Matador Production Company	288	63
Chevron USA Inc.	264	189
Hilcorp Energy Company	203	0
ConocoPhillips Company/Burlington Resources	161	112
WPX Energy	148	21
Kaiser-Francis Oil Company	131	67
Lime Rock Resources Ii-A, L.P.	129	91

This excerpted table shows the oil and gas companies that fracked the greatest number of oil and gas wells in New Mexico with trade secret chemicals and trade secret surfactants between January 1, 2013 and September 29, 2022. The full table showing all of the companies that fracked at least one well with trade secret chemicals and trade secret surfactants between January 1, 2013, and September 29, 2022, is located in the appendix. The wells injected with trade secret surfactants are a subset of the wells injected with trade secret chemicals. For a more detailed explanation of data sources, see the Appendix.

Erratum: The heading for the middle column in Table 6 on page 15 was corrected to show that the numbers in that column reflect the number of wells injected with trade secret chemicals, 2013-2022.

Table 7. Oil and Gas Companies that Fracked Wells in New Mexico Using Nonionic Fluorosurfactants, 2013-2022

Well Operator	Number of wells injected with nonionic fluorosurfactants	Total weight of fluorosurfactants (lbs.)
Chevron USA Inc.	11	46
Apache Corporation	5	90
XTO Energy/ExxonMobil	4	814
COG Operating LLC	2	16
Nadel and Gussman Permian, LLC	1	<1
Seely Oil Co.	1	ND

This table shows the oil and gas companies that fracked oil and gas wells in New Mexico with unspecified nonionic fluorosurfactants between January 1, 2013 and September 29, 2022. The wells injected with the unspecified nonionic fluorosurfactants are a subset of the wells injected with trade secret chemicals and the wells injected with trade secret surfactants. For a more detailed explanation of data sources, see the Appendix.

ND=No Data Available

c. Examples of Individual Wells Injected with PFAS, Trade Secret Chemicals

Industry-disclosed data have allowed PSR to identify multiple types of fracking chemicals, including trade secret substances, that are injected into individual wells, as well as the quantities used. In some cases, oil and gas companies injected hundreds or even thousands of pounds of PFAS or trade secret chemicals into oil and gas wells for fracking. If the toxicities of some of these chemicals were similar to those of PFOA or PFOS, these quantities would be enough to contaminate vast amounts of water. Table 8 provides examples of the chemicals reported in several New Mexico wells.

Table 8. Examples of Chemical Reporting on Individual Oil and Gas Wells in New Mexico

Well Operator	Well Number	County	Year Fracking Completed	Chemical as Identified	CAS Number	Trade Name	Mass (lbs.)
EOG Resources, Inc.	3002542386	Lea	2015	fluoroalkyl alcohol substituted polyethylene glycol	65545-80-4	Plexflow RTS	120
XTO Energy/ ExxonMobil	3002542709	Lea	2015	nonionic fluorosurfactant	trade secret	S-222	226
XTO Energy/ ExxonMobil	3001542928	Eddy	2018	PTFE	9002-84-0	not reported	394
DJR Operating, LLC	3004321335	Sandoval	2020	surfactant 1	trade secret	FN2-02	29,400
Apache Corporation	3001545800	Eddy	2021	Surfactant Blend	trade secret	FRAQ SLIQ PFR-5560	4,559

This table shows illustrative samples of specific oil and/or gas wells injected with the types of fracking chemicals referenced in the larger tables above, including the identified PFAS fluoroalkyl alcohol substituted polyethylene glycol, fluorosurfactants, the identified PFAS PTFE, and trade secret surfactants such as “surfactant 1.” The examples cover a range of years and represent wells fracked in several New Mexico counties. For a detailed explanation of data sources, see the Appendix

CH. 4 EXPOSURE PATHWAYS TO PFAS ASSOCIATED WITH OIL AND GAS OPERATIONS IN NEW MEXICO

a. Evidence of Oil and Gas Drilling-Related Spills

The potential in New Mexico for water contamination from PFAS or other chemicals used in oil and gas operations is not just hypothetical. In 2017, the news outlet EnergyWire reported on spills at oil and gas sites in New Mexico and other states that had occurred over a five-year period. EnergyWire found 847 reported spills in New Mexico in 2012, 777 in 2013, 1,303 in 2014, 1,471 in 2015, and 1,311 in 2016.[129] According to the Center for Western Priorities, oil and gas companies operating in New Mexico reported 1,368 liquid spills in the state in 2021. The total volume spilled in 2021 was more than 4.7 million gallons, of which more than four million gallons was "produced water."[130] The remaining roughly 660,000 gallons was oil. New Mexico considers produced water to be a mixture that flows out of oil and gas wells, made up of the naturally occurring water from underground and "flowback" or wastewater from drilling and/or fracturing injected into the well that returns to the surface.[131] As such, produced water in New Mexico could contain PFAS or other man-made chemicals added to drilling and/or fracking fluid as well as naturally occurring contaminants found in the formation water such as radioactive substances.[132]

The EPA has indicated that oil can also contain residues of chemicals used in oil wells.[133] Therefore, it is possible that spills of produced water or oil could contain PFAS, even small amounts of which could cause significant and dangerous contamination. A review of New Mexico Oil Conservation Division records by the Center for Biological Diversity and WildEarth Guardians found that the number of spills reported in 2022 increased to more than 1,450.[134]

In 2019, a well operated by Enduring Resources, located in the exterior boundaries of the Counselors Chapter of the Navajo Nation Government,[135] spilled almost 60,000 gallons of oil and oil and gas wastewater.[136] A report prepared by a consultant for Enduring Resources found that the spill entered two tributaries of Escavada Wash and that groundwater in the area is less than 50 feet below the ground surface.[137] The New Mexico Bureau of Geology & Mineral Resources suggests that a wash is a wide, shallow streambed that is dry most of the time and that washes are similar to arroyos.[138] A state report found that the spill impacted groundwater or surface water – the report did not specify which type.[139] A 2018 report from the New Mexico Bureau of Geology and Mineral Resources suggests that the spill would have been likely to contaminate groundwater in part because "it is considered that a depth-to-water of less than 50 ft has high susceptibility" to contamination from oil and gas-related spills and because "[a]rroyo and valley bottoms are uniformly considered to be high susceptibility" for groundwater contamination following such spills.[140]

One particularly high-profile spill occurred in January 2020 when a pipeline carrying produced water burst at night, awakening Penny Aucoin and her husband Carl George and showering their home in Otis, New Mexico with wastewater for an hour. Aucoin told the NM Political Report that she was forced to euthanize 18 chickens and a dog and give up her remaining goat. She added that a county official informed her that she could not eat her chicken eggs or the chickens' meat and that she probably should avoid eating anything grown on her property. She and her husband reached a settlement[141] with the company that owned the pipeline, WPX Energy,[142] but Aucoin said that she remained concerned. She said during a news conference in January 2021,

> The dispute has been resolved amicably, but what scares me now is that people are blissfully unaware of the dangers that come with fracking, including the enormous amount of flow back waste [produced water] produced during the fracking process.

Aucoin said that she would be moving out of the area.[143]

b. Disposal of Wastewater Raises Pollution Concerns

The risk that PFAS and other chemicals could pollute the environment through the disposal of produced water is especially high because of the huge volumes involved. State data show that in 2022, the volume of produced water from New Mexico's oil and gas wells was almost 85 billion gallons, up from 67 billion gallons in 2021, and 57 billion gallons in 2020.[144]

According to a presentation by the state Environment Department, as of 2019, the most common method of produced water disposal was underground injection into wells that carry the wastewater into "deep, isolated geologic formations."[145] About 10 percent of the produced water was reused in oil and gas fields, where wastewater from oil and gas wells can be injected into oil wells to facilitate oil production in a process known as enhanced oil recovery or EOR. The surge of drilling in the Permian Basin has increased the generation of produced water and the need for more underground injection wells. Earthworks reported that

> [a]s of December, 2019, New Mexico had 983 active Class II disposal wells and 3,249 Class II EOR wells, for a total of 4,232. With the rapid expansion of Permian Basin development, the number of injection well permit applications has dramatically risen over time, with 538 new applications in 2019.[146]

If even a small percentage of the staggering amount of wastewater injected underground were tainted with PFAS, it could create significant pollution should it enter groundwater or surface water.

That fear is not unfounded; researchers have known for decades that produced water from injection wells can contaminate groundwater. In some cases, the produced water has migrated upward from deep underground, moving through nearby oil and gas wells, many of which have ceased operating but have not been properly sealed off from the surrounding underground rock formations.[147] This migrating wastewater can break out of abandoned wells and contaminate groundwater near the earth's surface.[148] In 1985, the Texas Department of Agriculture reported that it had a name for this phenomenon: "saltwater breakout," a reference to the high salt content of produced water.[149] The department quoted the Congressional Office of Technology Assessment regarding the "insidious" problem of underground injection of oil and gas wastewater. The Congressional office noted that such wastewater is typically injected in exactly the places where prior drilling has created opportunities for the wastewater to migrate into groundwater.[150] The department further reported that produced water could contaminate groundwater through leaks in an injection well's steel or cement casing, designed to seal the well off from groundwater supplies.[151] The consequences of such events are particularly acute in New Mexico with its heavy reliance on groundwater.

In 1989, Congress' investigative arm, the General Accounting Office (now the Government Accountability Office) found multiple cases of water contamination linked to underground injection wells, including in New Mexico. The agency cited a case in Lea County where leaks in the casing of an injection well operated by Texaco caused contamination of a farm.

> During the 1970s, 20 million gallons of salt water leaked from a Texaco disposal well in Lea County, New Mexico, into portions of a drinking water source, the Ogallala aquifer. Some of the brine made its way into a rancher's irrigation well, damaging his crop and, according to the rancher, ultimately causing the foreclosure of his farm property. On the basis of the results of a pressure test, the rancher successfully sued Texaco in 1977 for damages. Texaco subsequently made repairs to the well, and it is now operating in compliance with UIC [underground injection control] regulations. Texaco was not required to clean the aquifer, however, because, according to the Chief of New Mexico's Environment Bureau, the cost could not be economically justified.[152]

New Mexico's Governor's Office reported in 2022 that there were 1,700 abandoned oil and gas wells on private and state land.[153] (It is unclear how many are on federal land in New Mexico.) The potential for contamination through these wells is cause for concern. The state plugs about 50

Oil and gas wastewater is dumped from a truck into one of a series of unlined pits at the R360 waste disposal facility outside Hobbs, New Mexico, 2019. Photo credit: Melissa A. Troutman.

wells per year, but the governor said that the rate would significantly increase as the result of a $43.7 million infusion from the federal Interior Department provided by the federal Infrastructure Investment and Jobs Act, passed in mid-2022.

Several other types of oil and gas waste disposal could pose serious risks to New Mexicans if the waste were contaminated with PFAS. One is the disposal of oil and gas waste in earthen pits known as impoundments. New Mexico has a well-documented history of groundwater contamination due to disposal of oil and gas waste in earthen pits. From the mid-1980s to 2003, the state's Oil Conservation Division found almost 7,000 cases of soil and water contamination from oil and gas waste pits and 400 cases of groundwater contamination.[154] This evidence prompted the state to enact the "pit rule" in 2008 that prohibited those unlined pits that were most likely to cause contamination, strengthened the standards for pit liners, mandated that all pits have a permit, and banned new pits within certain distances of water resources and homes.[155] New, permanent and temporary pits, for example, were prohibited within 1,000 feet of homes, schools, or drinking water wells used by five or more families.[156] According to Earthworks, the pit rule was effective in reducing contamination: In its first two years of operation, there were no groundwater violations at pits covered by the rule. Meanwhile, oil and gas drilling expanded in the state, indicating that the rule did not hinder oil and gas extraction.[157]

However, in 2013, after opposition to the pit rule from the oil and gas industry, lawmakers passed new legislation relaxing protections. As a result, companies can now locate temporary pits containing "low chloride" fluid within 100 feet of perennial water courses, 200 feet from springs, wells or lakes, and 300 feet from homes or schools.[158] Such fluid with low chloride levels could pose risks if it were tainted with other toxics such as PFAS. Whereas the pit rule prohibited burying of waste at well sites unless the waste met more stringent health and environmental standards (e.g. benzene levels in temporary pits 50-100 feet above groundwater could not exceed 0.2 parts per million),[159] the new rule allows burying at well sites of waste under much more permissive standards (benzene levels in temporary pits 51-100 feet above groundwater cannot exceed 10 parts per million).[160] As indicated by these standards, this waste often contains dangerous contaminants including carcinogenic hydrocarbons such as benzene.[161] This report suggests that the waste could contain PFAS, too. Neither the pit rule nor the new rule mention PFAS, but by allowing for the more permissive treatment of oil and gas waste, the new rule increases the risk of contamination from waste that could contain these highly toxic and persistent pollutants.

Earthworks identified other methods of oil and gas waste disposal in New Mexico that could pose risks for PFAS contamination including taking the waste to treatment plants, recycling facilities, landfills, and "landfarms," where contaminated soils, drill cuttings, and tank bottoms are allowed to be spread over land.[162]

c. Volatilizing, Flaring Could Pollute Air with PFAS

PFAS used in oil and gas wells could follow airborne exposure routes, according to toxicologist David Brown, former director of environmental epidemiology at the Connecticut

A poorly lit flare at Rustler Breaks SWD #6/ API #30-015-45034, a San Mateo Midstream facility in Eddy County, New Mexico, Sept. 2022. Photo credit Charlie Barrett, Earthworks.

Department of Health who has investigated health effects associated with unconventional gas drilling with the Southwest Pennsylvania Environmental Health Project. He warned that if PFAS were to enter drinking water, it could subsequently volatilize or become airborne inside homes. Brown also added another potential pathway for airborne exposure: PFAS could become airborne when gas is burned off during flaring at the wellhead or vented unburned at the wellhead.[163]

Flaring and venting are used extensively in New Mexico, suggesting that airborne PFAS through these pathways could be a risk in the state. The Howard Center for Investigative Journalism analyzed satellite data and found that between 2012 and 2020, oil and gas operators on federal land in New Mexico flared more than 138 billion cubic feet of gas,[164] enough to power more than 1.1 million homes for a year, according to a home energy consumption estimate by Popular Science magazine.[165] Gas is flared or vented unburned in emergencies and when there is insufficient pipeline capacity to bring the gas to market.[166] Insufficient pipeline capacity has been an issue in the Permian Basin in recent years when oil prices were much higher than gas prices, leaving oil and gas companies with little incentive to build pipelines to transport and sell the gas that was extracted along with the oil.[167] Soaring gas prices due to the war in Ukraine may change that equation, but it takes time to construct pipelines, and gas may not be captured if it cannot be transported to market.

In 2021, New Mexico enacted rules designed to reduce flaring and venting of gas.[168] However, some New Mexicans are skeptical that the rules can be enforced, considering that New Mexico had only 11 well inspectors as of end-2022 but 51,000 operating oil and gas wells.[169] Continued flaring and venting may provide another pathway for PFAS contamination from oil and gas wells.

Louisiana-based chemist Subra told PSR that the risk of airborne PFAS exposure might even be an issue for people living hundreds of miles from oil and gas fields.[170] Noting that gas from across the nation is delivered via pipeline to liquefied natural gas (LNG) facilities in Louisiana and Texas on the coast of the Gulf of Mexico, she proposed that residents of these communities ought to know if they are being exposed to PFAS in the gas from air emissions related to transforming the gas into a liquid for export. Bolstering Subra's concern, Reuters reported that in 2020, an LNG export facility in Corpus Christi, Texas operated by Cheniere Energy, Inc., exceeded permitted limits for air emissions in 293 instances. At least some of the emissions were volatile organic compounds from chemicals removed from the natural gas during the liquefaction process.[171] Reuters did not report that PFAS was released, but it is unclear whether anyone monitored for it. Some of the gas to be exported as LNG that could contain PFAS may arrive at the Gulf Coast from New Mexico. The Energy Information Administration reported in 2022 that three new pipelines will allow gas producers in the Permian basin to reach LNG export facilities on Texas's Gulf Coast.[172]

CH. 5 HEALTH STUDIES LINK OIL AND GAS OPERATIONS TO ILLNESS

a. Oil, Gas Well Proximity Associated with Disease

Peer-reviewed studies of people living near oil and gas operations have found that proximity to active well sites correlates with a variety of diseases and other health effects. While studies are lacking on health effects in New Mexico, a 2021 study of more than three million pregnant women in Texas showed that living within one kilometer of an active oil or gas well increased the odds of gestational hypertension (high blood pressure) and eclampsia[173] (a pregnancy-related high blood pressure disorder that can induce seizures or coma).[174] A 2020 study of pregnant women living in the Eagle Ford Shale area of South Texas found that exposure to a high number of nightly flaring events was associated with a 50 percent increase in the risk of preterm birth.[175] A 2020 study in Texas documented a link between natural gas drilling and production from both conventional and unconventional wells and frequency of hospitalization for childhood asthma.[176] Several studies conducted in Colorado, another major producer of oil and gas, also found associations between proximity to oil and gas operations and health effects, including congenital heart defects in newborns[177] and cancer diagnoses among Coloradans from birth to 24 years old.[178]

PSR has collaborated with Concerned Health Professionals of New York to compile and summarize the substantial and growing number of scientific studies that have found serious health effects associated with oil and gas operations. In the eighth edition (2022) of our report, we wrote,

> Public health problems associated with fracking include prenatal harm, respiratory impacts, cancer, heart disease, mental health problems, and premature death.... Poor birth outcomes have been linked to fracking activities in multiple studies in multiple locations using a variety of methods. Studies of mothers living near oil and gas extraction operations consistently find impaired infant health, especially elevated risks for low birth weight and preterm birth. As we go to press, a new study in Pennsylvania finds "consistent and robust evidence that drilling shale gas wells negatively impacts both drinking water and quality of infant health."[179]

Low birthweight is a leading contributor to infant death in the United States.[180]

Many residents living near oil and gas operations have reported serious health concerns while expressing frustration over the secrecy surrounding chemicals used by the oil and gas industry.[181] In 2020, Pennsylvania's Attorney General issued a report based on a criminal grand jury investigation of oil and gas drilling pollution in the Keystone State. Drilling for gas in shale formations has surged in that state over the past 15 years,[182] vaulting it into the number two spot among gas-producing states (Texas is number one)[183] and bringing many more Pennsylvanians into contact with gas drilling and its impacts. Based on testimony from over 70 households, the attorney general compiled evidence of serious health impacts, finding that

> Many of those living in close proximity to a well pad began to become chronically, and inexplicably, sick. Pets died; farm animals that lived outside started miscarrying, or giving birth to deformed offspring. But the worst was the children, who were most susceptible to the effects. Families went to their doctors for answers, but the doctors didn't know what to do. The unconventional oil and gas companies would not even identify the chemicals they were using, so that they could be studied; the companies said the compounds were "trade secrets" and "proprietary information." The absence of information created roadblocks to effective medical treatment. One family was told that doctors would discuss their hypotheses, but only if the information never left the room.[184]

b. Studies Needed on PFAS

PSR is not aware of published studies that have analyzed well sites for PFAS or that have analyzed health effects related to potential use of PFAS at well sites. This lack of testing is not surprising; there were few if any grounds to

Angel Peak Scenic Area, Farmington, New Mexico, May 2012. New Mexico's natural beauty is well worth protecting. Photo credit: Judy Gallagher, https://creativecommons.org/licenses/by/4.0/.

test for PFAS in connection with oil and gas operations prior to July 2021, when PSR first publicized the probable use of these chemicals in oil and gas extraction. Now that we know PFAS have been used in oil and gas operations for years, scientists should determine whether there are connections between this use and health effects, for PFAS chemicals individually and as a compounding factor in conjunction with exposure to other fracking chemicals.

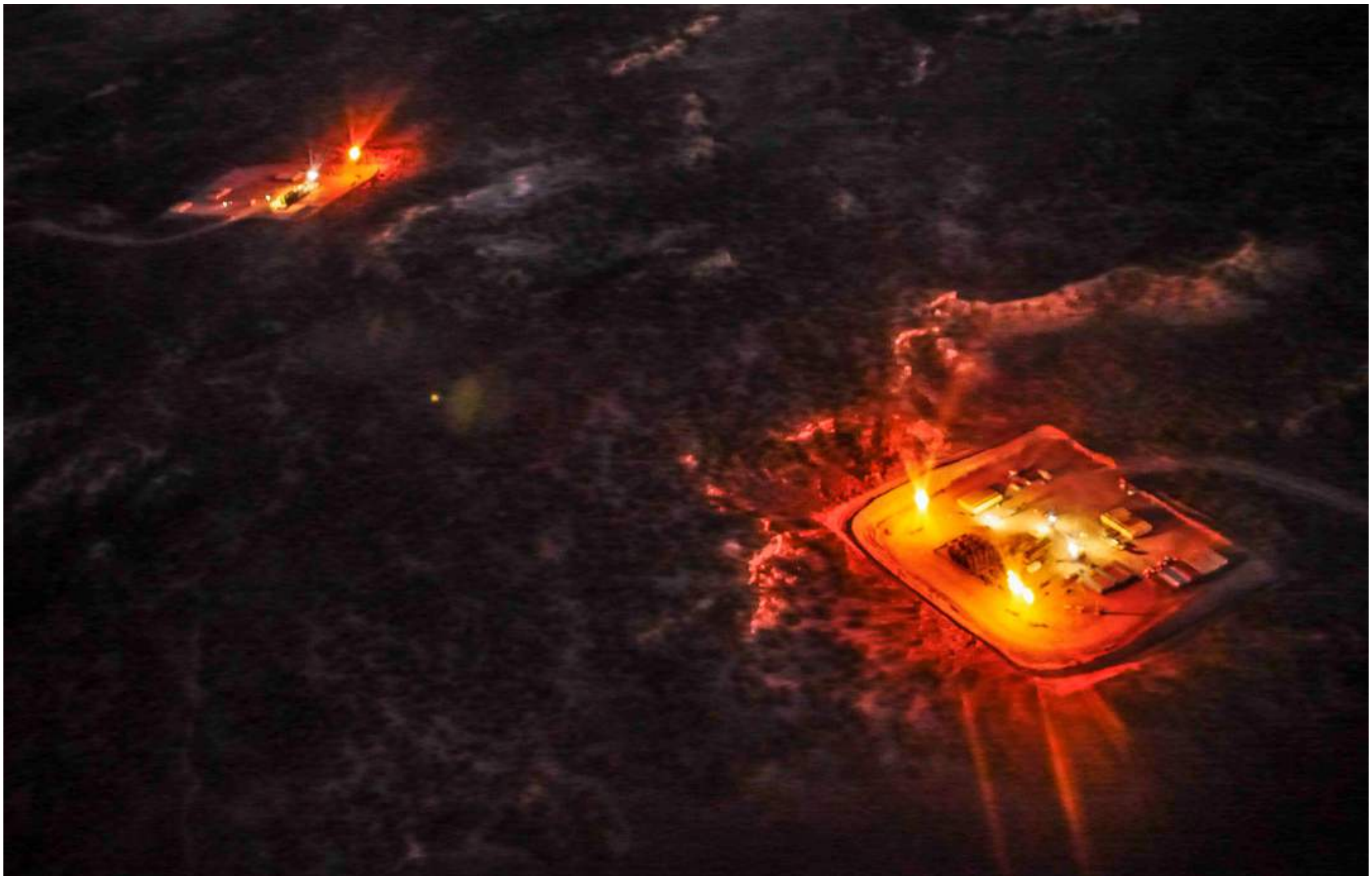
CH. 6 OIL & GAS-RELATED CHEMICAL EXPOSURE AS AN ENVIRONMENTAL JUSTICE ISSUE

a. Disproportionate Impacts on Environmental Justice Communities

“Fenceline” communities – people living close to oil and gas operations – often bear a disproportionate risk of exposure to toxic chemicals and thus may be particularly at risk from PFAS used in oil and gas extraction. Although drilling and fracking take place in the majority of U.S. states, not everyone shares in the risks equally. Rather, oil and gas infrastructure and associated chemicals are frequently located in or adjacent to lower-income, underserved, and marginalized communities, notably Black, Indigenous, and other communities of color.

In 2021, researchers used satellite observations and census data to show that 83 percent of the flaring from unconventional oil and gas wells in the contiguous United States between March 2012 and February 2020 took place in three basins: the Permian Basin in New Mexico and Texas, the Williston Basin in North Dakota, and the Western Gulf Basin in southern Texas and Louisiana. They estimated that over half a million people in these basins lived within three miles of a flare, with 39 percent of them living near more than 100 flares each night. The researchers also reported that in these regions, Black, Indigenous, and people of color were disproportionately exposed to flaring.[185]

Other studies have also found disproportionate impacts on people of color. A 2020 study found that compared to white residents, Hispanic residents living in the Eagle Ford shale region of Texas were disproportionately exposed to



Nighttime flaring, just north of Chaco Culture National Historical Park near Nageezi, New Mexico, Oct. 2014. Photo credit: Dom Smith, EcoFlight.

flaring from unconventional oil and gas wells, even though they were less likely than white residents to live near unconventional oil and gas wells.[186] In 2016, a public health research team showed that in the Eagle Ford shale region, disposal wells for fracking wastewater were more than twice as common in areas where residents were more than 80 percent people of color than in majority-white communities. They also found that disposal wells were disproportionately located in areas with high rates of poverty, but even in these areas, the association with race was predominant. "Adjusting for both poverty and rurality," the researchers wrote, "we still found that as the proportion of people of color in the census block group increased, so did the presence of disposal wells." Since 2007, they reported, Texas had permitted more than 1,000 waste disposal wells in the Eagle Ford Shale region, where groundwater is the primary source of drinking water.[187]

A 2019 analysis conducted in Colorado, Oklahoma, Pennsylvania, and Texas found strong evidence that African Americans disproportionately lived near fracking wells in Texas and Oklahoma, while Hispanics disproportionately lived near fracking wells in Texas and urban Colorado. "The question, who bears the costs of unconventional natural gas drilling, is of great relevance not only for the U.S., but worldwide," the researchers wrote.

b. Navajo Survey Shows Health Impacts

All chapters of the Navajo Nation in New Mexico were identified in 2020 as "environmental justice" communities by the United States Bureau of Land Management.[188] In 2021, the Counselor Chapter of the Navajo Nation in New Mexico conducted a health and cultural survey regarding oil drilling operations in the Counselor, Torreon, and Ojo Encino chapters that identified health risks and distrust of regulators and oil companies. The chapter conducted its health survey under the guidance of the Southwest Pennsylvania Environmental Health project, which had conducted similar surveys in other communities with oil and gas drilling. Among other things, the chapter measured the levels of fine particulate matter ($PM_{2.5}$) through air monitors near people's

Table 9. Wells on NM Federal, State, and Tribal Land Fracked with PFAS and Possible PFAS, 2013-2022

Type of fracking chemical injected	No. Wells in state	Total Mass in state (lbs.)	No. Wells on Federal Land	Total Mass Federal Land (lbs.)	No. Wells on State Land	Total Mass State Land (lbs.)	No. Wells on Tribal Land	Total Mass Tribal Land (lbs.)
	9066	--	4468	--	2350	--	192	--
Trade Secret chemicals	8293	243,000,000	4072	115,000,000	2153	54,600,000	186	2,040,000
Trade Secret surfactants	3681	19,300,000	1813	10,900,000	954	4,740,000	86	230,000
Fluoro-surfactants	24	965	12	790	10	164	0	0.0
65545-80-4	34	6,400	8	1,370	17	3,060	0	0.0
PTFE	227	2,610	113	1,650	53	552	3	data not available

This table shows the number of oil and gas wells in New Mexico -- statewide, on federal land, on state-owned land, and on tribal land – that oil and gas companies fracked between 2013 and 2022 with at least one trade secret chemical, at least one trade secret surfactant, at least one fluorosurfactant, fluoroalkyl alcohol substituted polyethylene glycol (CAS Number 65545-80-4, a known PFAS), or PTFE (a known PFAS). The total weight figures reflect the sum of all records for which PSR has enough information to calculate a chemical's weight. For a detailed explanation of data sources, see the Appendix.

homes on the side of the home nearest to the closest oil wells. The readings showed the $PM_{2.5}$ levels, generally recorded between peak releases, were significantly higher at six of eight measuring sites compared to median levels in other non-Navajo communities with oil and gas operations. Residents living near a source of such air pollution are at greater risk for contracting or intensifying respiratory or cardiovascular diseases.[189] In a survey of health symptoms of 80 residents of the Counselor Chapter, more than 60 percent reported 11 symptoms during the year after drilling began near their homes, including sore throat, cough, and sinus problems. This number of reported health symptoms was greater than the number reported by respondents living near oil and gas wells in other communities in the U.S.[190] Separately, the Chapter conducted a cultural survey regarding the effects of oil drilling, collecting data from 136 randomly selected adults in the three chapters. Among other findings, 104 respondents strongly agreed with the statement, “Our local leaders have spoken out against drilling and no one at the tribal, state or federal level, including BLM and BIA, has listened.” One hundred and seventeen strongly agreed with the statement, “The oil companies have no respect for land, people & life.”[191]

PSR found that about 97 percent of the wells in New Mexico drilled on tribal land for which oil and gas companies disclosed the use of fracking chemicals were injected with at least one trade secret fracking chemical. This percentage was a bit higher than for wells drilled statewide (about 91 percent). But the total number of wells drilled on tribal land was much smaller, so it is unclear whether this difference was statistically significant.

Where a pattern of risks affects people of color and/or lower-income people disproportionately, oil and gas production methods should be viewed and addressed as an Environmental Justice issue. So too should any oil and gas-related exposure to PFAS.

CH. 7

POLICY CAN HELP PROTECT NEW MEXICANS FROM PFAS IN OIL & GAS OPERATIONS

a. Modest Federal Protections from PFAS Pollution

Governments at all levels will have to do more to protect the public from PFAS, in large part because EPA has taken only modest steps to do so, while Congress and the executive branch have exempted the oil and gas industry from major provisions of multiple federal environmental laws. For example, oil and gas waste is exempted from the hazardous waste rules that require cradle-to-grave tracking and safe handling of hazardous substances under the Resource Conservation and Recovery Act. These exemptions increase the burden on state governments to address any PFAS pollution associated with oil and gas extraction.[192]

EPA has taken some steps to protect the public from dangerous PFAS. In 2005, EPA reached a then-record $16.5 million settlement with chemical manufacturer Dupont after accusing the company of violating the federal Toxic Substances Control Act (TSCA) by failing to disclose information about PFOA's toxicity and presence in the environment.[193] In 2006, EPA invited Dupont, 3M and six other companies to join a "stewardship" program in which the companies promised to achieve a 95 percent reduction of emissions of PFOA and related chemicals by 2010, compared to a year 2000 baseline. The agreement also required the companies to eliminate such emissions and use of these chemicals by 2015.[194] In 2022, EPA said on its website that the companies reported that they had accomplished those goals, either by exiting the PFAS industry or by transitioning to alternative chemicals.[195] EPA reported in 2022 that the manufacture and use of at least one PFAS, PFOA, had been phased out in the U.S., and that no chemical company had reported making PFOS in the U.S. since 2002. EPA noted that existing stocks of PFOA might still be used, and imported products may contain some PFOA.[196] A 2020 scientific article reported that PFOA was still used in Asia.[197] EPA stated that limited ongoing uses of PFOS remain.[198] Since the announcement of its PFAS stewardship program in 2006, EPA has allowed nearly unlimited use of closely related "replacement" chemicals in dozens of industries.[199] In response, in 2015 a group of more than 200 scientists raised health and environmental concerns that the new PFAS designed to replace PFOA and PFOS may not be safer for health or the environment.[200]

In October 2021, EPA announced a "strategic roadmap" for regulating PFAS. This plan encompasses a goal of setting federal drinking water standards for several PFAS chemicals by 2023, as well as commitments to "use all available regulatory and permitting authorities to limit emissions and discharges from industrial facilities" and "hold polluters accountable."[201] The plan does not, however, include an examination of PFAS use in the oil and gas industry. (Later that month, 15 members of the U.S. House of Representatives asked EPA to examine this topic.[202] The month before, PSR asked EPA to collect data on PFAS use in oil and gas extraction, utilizing its authority under TSCA.[203] As previously stated, in June 2022, EPA announced new health advisory levels for several types of PFAS; unfortunately, these standards are advisory and not legally enforceable.[204] In August 2022, EPA proposed designating PFOA and PFOS as hazardous under Superfund.[205] This designation would enable affected parties to more easily hold oil and gas companies accountable for cleanup costs if PFOA and PFOS were found at oil and gas sites because under Superfund, liability does not require negligence, and any potentially responsible party (PRP) can be held liable for cleanup of an entire site when it is difficult to distinguish contributions to pollution among several parties. As EPA writes about Superfund, "[i]f a PRP sent some amount of the hazardous waste found at the site, that party is liable."[206] Finally as previously stated, in March 2023, EPA announced a plan to regulate six types of PFAS in drinking water.

In acting belatedly to regulate at least some types of PFAS in drinking water, EPA is following the lead of several states. As of 2023 nine states, including at least several with contaminated military sites, had developed enforceable standards for concentrations of several types of PFAS in drinking water.[207] One of those to act is Michigan, which set standards in 2020 for limiting PFAS in drinking water and for removing PFAS from groundwater. The standards apply to PFOA and six other forms of PFAS. Michigan's maximum allowable level is no more than eight parts per trillion for PFOA,[208] a standard that is one of the lowest among states but is now much more permissive than EPA's interim health advisory level. Even Michigan's standard, however, shows how toxic PFAS can be. By extrapolation, Michigan's standard suggests that one measuring cup of PFOA could contaminate almost eight billion gallons of water – the amount of water needed to fill almost 12,000 Olympic-sized swimming pools at about 660,000 gallons per pool.[209]

b. New Mexico Disclosure Rules: In Need of Sweeping Reform

In New Mexico, multiple reforms are needed to protect the public from the use of PFAS in oil and gas operations, including changing the state's chemical disclosure rules to lift the veil of secrecy that oil and gas companies have used to conceal the use of potentially dangerous chemicals including, perhaps, PFAS. One such change should be tighter limits on the use of trade secret provisions.

Oil and gas companies have argued that chemical trade secrets are necessary to protect their intellectual property from competitors. However, this interest does not have to mean a complete withholding of information on chemical identities from scientists, regulators, and the public. In 2015, California, a major oil-producing state,[210] began requiring full disclosure of chemicals used for well stimulation, including fracking. The policy did away with trade secret exemptions for the individual chemicals used in fracking products.[211] In June 2022, Colorado, a major producer of oil and gas,[212] followed in California's footsteps but extended the disclosure requirements to all chemicals used in oil and gas wells, not just fracking or stimulation chemicals.[213]

The methodology utilized in California and Colorado is consistent with a recommendation issued in 2014 by an advisory panel to the U.S. Department of Energy: that companies reveal the fracking chemicals injected into each well, providing that information in a list in which the chemicals are disassociated from the trade name of the commercial products they are part of.[214] This form of disclosure enables the public to know all the chemicals used in fracking without disclosing to rival chemical manufacturers the exact components of proprietary formulas.[215] In a similar way, food producers keep recipes secret while disclosing individual ingredients, enabling the public to know the contents of food products but making it difficult for rival producers to recreate valuable food brands. In addition, California has a process under which state regulators review secrecy requests from chemical companies to determine whether the information must be kept proprietary.[216] Health and safety data related to fracking fluids are not allowed to be hidden from public view under California law.[217] California also requires disclosure of fracking chemicals before fracking begins,[218] as do West Virginia[219] and Wyoming.[220]

New Mexico should also ensure that full chemical disclosure is required from all the companies in the chemical supply chain. Currently, New Mexico rules require chemical disclosure from the well operator.[221] Chemical manufacturers, however, are exempted from this reporting, despite being the only entity that always knows the precise contents of the chemicals they produce. Not only does New Mexico omit chemical manufacturers from disclosure requirements and allow them to claim trade secrets; it also limits their responsibility by providing that the Division of Oil and Gas "does not require the reporting of information beyond the material safety data sheet data as described in 29 C.F.R. 1910.1200." This provision means that disclosure is limited to what is required on material safety data sheets (now called safety data sheets) on which chemical manufacturers list information about their chemicals to protect workers. Well operators are not responsible for compiling chemical information from manufacturers that is not disclosed on the sheets.[222] As several Harvard researchers reported in 2013, manufacturers can legally omit chemical information from the sheets. For example, if a chemical has not been tested and found to be hazardous, it does not need to be disclosed, even if tests would show that it is hazardous.[223] Therefore, the manufacturers could effectively withhold this information from public disclosure with or without trade secret protection.


Flaring near Chaco Culture National Historic Park, Dec. 2014. Photo credit: Jane Pargiter, EcoFlight.

Evidence suggests that chemical manufacturers do not always tell companies farther down the supply chain the full contents of the chemical products they are using; rather, they provide these companies with vague descriptions, generic chemical family names or, as the Harvard researchers suggested, Material Safety Data Sheets with an incomplete list of chemicals.[224] In such cases, the end users may legitimately be unable to disclose all the identities of chemicals – including PFAS – used at a particular well, whether under trade secret protection or not. They simply would not have the information. Requiring disclosure of oil and gas chemicals by chemical manufacturers would avoid this problem. Colorado took this step in its June 2022 legislation.[225]

These reasonable and feasible reforms are valuable steps to protect the health of people who may be exposed to PFAS and other dangerous oil and gas chemicals, be they industry workers, residents living near well sites, or first responders called to the scene of an accident. They can improve health and potentially save lives. Additional steps to reduce the harms caused by oil and gas extraction are outlined in the following section, including a ban on the use of PFAS in oil and gas operations, an action that Colorado took in 2022.[226] Among the evidence supporting the feasibility of this measure is a peer-reviewed analysis published in 2021 showing that many PFAS are immediately replaceable with less-persistent and less-toxic substances, including for use in the oil and gas industry.[227]

c. New Mexico Hazardous Waste Rules Also in Need of Reform

New Mexico's state government has recognized the dangers of PFAS but, in doing so, has illuminated another gap in state rules that should be closed to protect the public from PFAS use in oil and gas operations. In 2021, Governor Michelle Lujan Grisham petitioned EPA to list the class of chemicals known as PFAS as hazardous under Subtitle C of the federal Resource Conservation and Recovery Act (RCRA) or, alternatively, "list individual PFAS chemicals under RCRA known to have harmful effects to humans and the environment."[228] Subtitle C of RCRA is our nation's law that requires safe management of hazardous waste from "cradle-to-grave."[229] Gov. Luhan Grisham emphasized how important this policy change would be for New Mexico, writing

> I implore EPA to do what is immediately necessary to protect the people and environment of the United States from the real and potentially devastating effects of exposure to PFAS....Without a uniform regulatory process addressing PFAS from manufacture to disposal, states like New Mexico will be left attempting to use a patchwork of statutory and regulatory authorities that may or may not provide enough oversight...[230]

EPA administrator Michael Regan replied later in 2021 that the agency would initiate a rulemaking process to declare four types of PFAS to be hazardous under RCRA: PFOA, PFOS, PFBS, and GenX. He also said that EPA would initiate a rulemaking to "clarify that emerging contaminants such as PFAS can be addressed through RCRA corrective action."[231]

Yet under both the federal RCRA[232] and the state's implementation of the federal law,[233] oil and gas wastes are exempt from hazardous waste requirements. This exemption likely means that even if EPA acted on the governor's petition and declared PFAS hazardous, oil and gas wastes containing PFAS would not be subject to hazardous waste protections. New Mexico could act to avoid this problem and regulate oil and gas waste as hazardous by following the example of New York State. In 2020, New York enacted legislation to designate oil and gas waste as hazardous.[234] State Senator Rachel May, one of the bill's sponsors, said in a statement,

> Wastewater from fracking can contain carcinogenic compounds and naturally occurring radioactive materials. The regulatory loophole that allowed waste from fracking and crude oil processing to be treated as standard industrial waste means it enters local sewage treatment facilities, sometimes with radiation levels hundreds of times the safe limit, it then flows directly back into our waterways – the source of drinking water for thousands of New Yorkers.[235]

May issued her statement before it was widely known that PFAS was used in oil and gas operations, but considering the oil and gas industry's record of using PFAS, these chemicals could be present in oil and gas wastes whether in New York, New Mexico, or other states. Continuing to exempt oil and gas wastes from hazardous waste treatment means that PFAS in these wastes would likely be exempt, too, with potentially serious consequences for New Mexicans.

RECOMMENDATIONS

In light of the findings shared in this report, PSR recommends the following:

- **Halt PFAS use in oil and gas extraction.** New Mexico should follow the lead of Colorado, a major oil- and gas-producing state that in June 2022 passed legislation banning the use of PFAS in oil and gas wells. Furthermore, New Mexico and the U.S. Environmental Protection Agency (EPA) should prohibit PFAS from being used, manufactured, or imported for oil and gas extraction. Many PFAS are replaceable with less-persistent and less-toxic alternatives.

- **Expand public disclosure.** New Mexico should greatly expand its requirements for public disclosure of oil and gas chemicals. TThe state could again follow the example offered by Colorado by requiring disclosure of all individual chemicals used in oil and gas wells, without exceptions for trade secrets, while still protecting chemical product formulas. New Mexico should also require disclosure on the part of chemical manufacturers and require chemical disclosure prior to permitting, as have California, West Virginia, and Wyoming.

- **Increase testing and tracking.** New Mexico and/or the U.S. EPA should determine where PFAS have been used in oil and gas operations in the state and where related wastes have been deposited. They should test nearby residents, water, soil, flora, and fauna for PFAS, both for the particular type(s) of PFAS used and for organic fluorine to detect the presence of other PFAS. and/or their breakdown products. Testing equipment should be used that is sensitive enough to detect PFAS at a level of single-digit parts per trillion or lower.

- **Require funding and cleanup**. Oil and gas and chemical firms should be required to fund environmental testing for PFAS in their areas of operation, and should PFAS be found, be required to fund cleanup. If water cleanup is impossible, companies responsible for the use of PFAS should pay for alternative sources of water for household and agricultural uses, as needed.

- **Remove New Mexico's oil and gas hazardous waste exemption.** New Mexico exempts oil and gas industry wastes from state hazardous waste rules. New Mexico should follow New York's lead and remove its state-level hazardous waste exemption for the oil and gas industry.

- **Reform New Mexico's regulations for oil and gas production wells and underground injection disposal wells.** The state should prohibit production wells and underground wastewater disposal wells close to underground sources of drinking water, homes, health care facilities and schools, require groundwater monitoring for contaminants near the wells, and for disposal wells, require full public disclosure of chemicals in the wastewater.

- **Transition to renewable energy and better regulation.** Given the use of highly toxic chemicals in oil and gas extraction, including but not limited to PFAS, as well as climate impacts of oil and gas extraction and use, New Mexico should transition away from oil and gas production and move toward renewable energy and efficiency while providing economic support for displaced oil and gas workers. As long as drilling and fracking continue, the state should better regulate these practices so that New Mexicans are not exposed to toxic substances and should empower local governments also to regulate the industry. When doubt exists as to the existence or danger of contamination, the rule of thumb should be, "First, do no harm."

APPENDIX

Data Sources for PFAS Used in New Mexico's Oil and Gas Wells

To identify where PFAS were used at oil and gas wells in New Mexico, PSR analyzed data from the state Oil Conservation Division that is part of the Energy, Minerals and Natural Resources Department. These data, based on reports from oil and gas well operators, show well-by-well which fracking chemicals were used.236 These data date from January 1, 2013 to early 2018, likely because a change in state rules in September 2017 required reporting to the FracFocus database rather than to the state.[237] PSR also relied on the well-by-well reports of fracking chemicals recorded in FracFocus, a database for the oil and gas industry[238] maintained by the Groundwater Protection Council,[239] a nonprofit comprised of regulators from state agencies. The dates of these records extend from January 1, 2013 to September 29, 2022. PSR consulted the open-source version of FracFocus, Open-FF,[240] which is more accurate and informative than the original version of FracFocus.[241]

Under current New Mexico law, operators must disclose the fracking chemicals used in each well to the FracFocus database using the "current edition of the hydraulic fluid product component information form published by FracFocus." Disclosure must occur within 45 days after hydraulic fracturing treatment.[242] Based on the disclosure forms available on FracFocus' website, operators must list, among other things, each individual chemical injected into the well and each chemical's CAS number, if available.[243] New Mexico's prior fracking chemical disclosure rules required disclosure of similar information.[244] There are, however, significant exceptions to disclosure requirements under New Mexico's rules, including an exception for chemicals designated a trade secret[245] that are discussed in Chapter 3 and Chapter 7.

Table 6. Oil and Gas Companies that Fracked Wells in New Mexico Using Trade Secret Chemicals and Trade Secret Surfactants, 2013-2022.

Operator	Number of wells injected with trade secret chemicals	Number of wells injected with trade secret surfactants
EOG Resources, Inc.	1177	214
COG Operating LLC	844	438
Devon Energy Production Company L. P.	586	358
Mewbourne Oil Company	575	116
Occidental Oil and Gas	498	141
XTO Energy/ExxonMobil	442	203
Apache Corporation	439	386
Cimarex Energy Co.	336	186
Matador Production Company	288	63
Chevron USA Inc.	264	189
Hilcorp Energy Company	203	0
ConocoPhillips Company/Burlington Resources	161	112
WPX Energy	148	21
Kaiser-Francis Oil Company	131	67
Lime Rock Resources Ii-A, L.P.	129	91
BTA Oil Producers LLC	121	27
Marathon Oil	108	3
Mack Energy Corp	105	76
RKI Exploration & Production, LLC	100	55
Burnett Oil Co., Inc.	99	47
BOPCO, L.P.	86	64
Yates Petroleum Corporation	84	71
LRE Operating, LLC	82	64
Encana Oil & Gas (USA) Inc.	76	40
Tap Rock Resources	73	1
Centennial Resource Production, LLC	70	10
DJR Operating, LLC	70	63
Energen Resources Corporation	68	20
Advance Energy Partners Hat Mesa LLC	53	22
Murchison Oil & Gas Inc	47	44
Dugan Production Corp.	46	27
Novo Oil & Gas Texas, LLC	44	39
Logos Operating, LLC	42	21
Franklin Mountain Energy	39	0
Enduring Resources LLC	36	26
Vanguard Permian LLC	34	14
BP America Production Company	33	16
OXY USA WTP Limited Partnership	33	23

Table 6. Oil and Gas Companies that Fracked Wells in New Mexico Using Trade Secret Chemicals and Trade Secret Surfactants, 2013-2022.

Operator	Number of wells injected with trade secret chemicals	Number of wells injected with trade secret surfactants
Titus Oil & Gas Production, LLC	30	16
Caza Operating, LLC	23	13
Endurance Resources LLC	23	22
Chisholm Energy Operating, LLC	21	2
Legacy Reserves Operating LP	21	10
Ameredev Operations LLC	20	5
EnerVest, Ltd.	20	19
SM Energy	18	2
Colgate Operating, LLC	16	1
Gmt Exploration Company LLC	15	14
BreitBurn Operating LP	14	8
Burlington Resources Oil & Gas Company LP	14	14
Nearburg Producing Co	14	14
Longfellow Energy, LP	13	9
Redwood Operating LLC	13	4
Percussion Petroleum LLC	12	10
Steward Energy II, LLC	12	7
Fasken Oil & Ranch Ltd	11	10
Nadel and Gussman Permian, LLC	11	10
Read & Stevens, Inc.	10	10
Whiting Petroleum	10	3
Linn Operating, Inc.	9	2
Cross Timbers Energy, LLC	8	6
Pride Energy Company	8	8
Strata Production Co.	8	6
Chesapeake Operating, Inc.	7	7
Elm Ridge Exploration Company LLC	7	0
Forty Acres Energy LLC	7	6
Legend Natural Gas Iii Limited Partnership	7	1
McElvain Energy, Inc.	7	5
Regeneration Energy, Corp	7	6
Alamo Permian Resources, LLC	6	5
Manzano LLC	5	4
V-F Petroleum Inc	5	3
Atlas Energy, L.P.	4	0
Avant Operating, LLC	4	0
Capstone Natural Resources, LLC	4	4
Lynx Petroleum Consultants Inc	4	4

Table 6. Oil and Gas Companies that Fracked Wells in New Mexico Using Trade Secret Chemicals and Trade Secret Surfactants, 2013-2022.

Operator	Number of wells injected with trade secret chemicals	Number of wells injected with trade secret surfactants
Marshall & Winston Inc	4	4
Premier Oil & Gas Inc	4	4
Rockcliff Energy Operating	4	0
Special Energy Corporation	4	4
Hadaway Consulting and Engineering, LLC	3	3
Nemo Fund I, LLC	3	3
Stephens & Johnson Operating Co.	3	1
Sundown Energy LP	3	0
Catena Resources Operating, LLC	2	2
Foundation Energy Management, LLC	2	2
IACX Production	2	2
ICA Energy Operating LLC	2	0
Koch Exploration Company, LLC	2	2
Maverick Operating, LLC	2	2
Memorial Resource Development LLC	2	0
OneEnergy Partners Operating, LLC	2	0
Quantum Resources Management, LLC	2	2
Sg Interests I Ltd	2	2
SIMCOE LLC	2	0
Texland Petroleum, LP	2	2
Thompson Engr & Prod Corp	2	1
Amtex Energy Inc.	1	0
BAM Permian Operating, LLC	1	1
BC Operating, Inc.	1	1
Boaz Energy, LLC.	1	1
Chuza Oil Company	1	1
Clayton Williams Energy Inc.	1	0
CML Exploration, LLC	1	1
Cobra Oil & Gas Corporation	1	1
D J Simmons Inc	1	1
DGP Energy	1	0
Forge Energy, LLC	1	1
Harvey E Yates Co	1	1
HEXP Operating, LLC	1	1
Hunt Cimarron Limited Partnership	1	1
Huntington Energy, LLC	1	0
ImPetro Operating LLC	1	1
Mammoth Exploration, LLC	1	1

Table 6. Oil and Gas Companies that Fracked Wells in New Mexico Using Trade Secret Chemicals and Trade Secret Surfactants, 2013-2022.

Operator	Number of wells injected with trade secret chemicals	Number of wells injected with trade secret surfactants
Mar Oil & Gas Corp.	1	0
Merit Energy Company	1	1
Merrion Oil & Gas Corp	1	1
Ridgeway Arizona Oil Corp.	1	0
Robert L. Bayless, Producer LLC	1	1
Running Horse Production Company	1	0
San Juan Resources, Inc.	1	0
Seely Oil Co	1	1
Tacitus LLC	1	0
Western Refining Southwest, Inc.	1	0

This table shows the oil and gas companies that fracked oil and gas wells in New Mexico with trade secret chemicals and trade secret surfactants between January 1, 2013 and September 29, 2022. The wells injected with trade secret surfactants are a subset of the wells injected with trade secret chemicals.

*ND = No data available.

New Mexico must strengthen its protections from PFAS and other pollution related to oil and gas extraction to safeguard its land and people. View from Deep Access Cave, Carlsbad Caverns National Park, Sept. 2020. Photo credit: Dan Pawlak, National Park Service.

ENDNOTES

[1] U.S. Environmental Protection Agency. Technical Fact Sheet: Drinking Water Health Advisories for Four PFAS (PFOA, PFOS, GenX chemicals, and PFBS). June 2022, at 4. Accessed Nov. 7, 2022, at https://www.epa.gov/system/files/documents/2022-06/technical-factsheet-four-PFAS.pdf.

[2] U.S. Environmental Protection Agency. Our Current Understanding of the Human Health and Environmental Risks of PFAS. Accessed Nov. 23, 2022, at https://www.epa.gov/pfas/our-current-understanding-human-health-and-environmental-risks-pfas.

[3] Toxic Synthetic "Forever Chemicals" are in Our Water and on Our Plates. NOVA (PBS) (Nov. 2, 2020). Accessed Sept. 5, 2022, at https://www.pbs.org/wgbh/nova/article/pfas-synthetic-chemicals-water-toxic/.

[4] U.S. Environmental Protection Agency. Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States. Washington, DC: Office of Research and Development; 2016, at 5-5 to 5-7. Accessed Mar. 13, 2023, at https://www.epa.gov/hfstudy.

[5] Dusty Horwitt. Fracking with Forever Chemicals. Physicians for Social Responsibility (July 2021), at 15. Accessed Sept. 8, 2022, at https://www.psr.org/wp-content/uploads/2021/07/fracking-with-forever-chemicals.pdf.

[6] Public Employees for Environmental Responsibility. Revealed: EPA Data on PFAS Sites (Oct. 17, 2021). Accessed Jan. 12, 2022, at https://www.peer.org/blog-revealed-epa-data-on-potential-pfas-sites/.

[7] U.S. Environmental Protection Agency. Master List of PFAS Substances. Polytetrafluoroethylene. CAS number 9002-84-0. Accessed Nov. 9, 2022, at https://comptox.epa.gov/dashboard/chemical/details/DTXSID7047724?list=PFASMASTER.

[8] U.S. Environmental Protection Agency. Master List of PFAS Substances. Poly(oxy-1,2-ethanediyl), .alpha.-hydro-.omega.-hydroxy-, ether with .alpha.-fluoro-.omega.-(2-hydroxyethyl) poly(difluoromethyl. CAS number 65545-80-4. Accessed Nov. 9, 2022, at https://comptox.epa.gov/dashboard/chemical/details/DTXSID6049727.

[9] American Chemical Society. CAS Registry. Accessed Sept. 5, 2022, at https://bit.ly/3nnGpv4.

[10] FracFocus. Chemical Names & CAS Registry Numbers. Accessed Sept. 5, 2022, at https://www.fracfocus.org/index.php/explore/chemical-names-cas-registry-numbers.

[11] The three chemists are Zacariah Hildenbrand, a research professor in Chemistry and Biochemistry at the University of Texas at El Paso, Kevin Schug, Shimadzu Distinguished Professor of Analytical Chemistry at the University of Texas at Arlington, and Wilma Subra, holder of a master's degree in chemistry and recipient of a John D. and Catherine T. MacArthur Foundation "Genius" Grant for her work helping to protect communities from toxic pollution. The board-certified toxicologist is Linda Birnbaum, former director of the National Institute of Environmental Health Sciences.

[12] Electronic mail communication with Linda Birnbaum (Mar. 6, 2023), telephone interview with Zacariah Hildenbrand (Mar. 6, 2023), electronic mail communication with Kevin Schug (Feb. 24, 2023), and electronic mail communication with Wilma Subra (Mar. 6, 2023).

[13] U.S. Department of Energy. Energy Information Administration. Crude Oil Production. Annual-Thousand Barrels. Accessed Dec. 20, 2022, at https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm.

[14] U.S. Department of Energy. Energy Information Administration. New Mexico Dry Natural Gas Production. Accessed Dec. 20, 2022, at https://www.eia.gov/dnav/ng/hist/na1160_snm_2a.htm.

[15] Tom DiChristopher. The Permian Basin in Texas and New Mexico will soon become the third-biggest oil producing region in the world: IHS Markit. CNBC (June 13, 2018). Accessed Dec. 20, 2022, at https://www.cnbc.com/2018/06/13/permian-will-soon-pump-enough-oil-to-be-opecs-2nd-biggest-producer.html.

[16] Adrian Hedden. Oil and Gas Drives Billions in Extra Funds for New Mexico in the Next Year. Carlsbad Current-Argus. Accessed Dec. 20, 2022, at https://www.currentargus.com/story/news/2022/12/16/oil-gas-drives-billions-funds-new-mexico-next-year-permian-basin-fossil-fuel-legislature-government/69721648007/.

[17] Miles O'Brien. The challenge of tracking methane emissions and why they are higher than publicly reported. PBS NewsHour. Accessed Dec. 20, 2022, at https://www.pbs.org/newshour/show/the-challenge-of-tracking-methane-emissions-and-why-they-are-higher-than-publicly-reported.

[18] U.S. Environmental Protection Agency. Research on Per- and Polyfluoroalkyl Substances (PFAS) (last updated Nov. 10, 2021). Accessed Nov. 7, 2022, at https://www.epa.gov/chemical-research/research-and-polyfluoroalkyl-substances-pfas. David Andrews and Bill Walker. Environmental Working Group. Poisoned Legacy (April 2015), at 6. Accessed Nov. 7, 2022, at https://www.ewg.org/research/poisoned-legacy. Andrew B. Lindstrom et al. Polyfluorinated Compounds: Past, Present, and Future. Environmental Science & Technology (2011), 45, 7954-7961, 7954. Accessed Nov. 7, 2022, at https://pubs.acs.org/doi/pdf/10.1021/es2011622.

[19] U.S. Environmental Protection Agency. What are PFCs and How Do

They Relate to Per- and Polyfluoroalkyl Substances (PFASs)? (Jan. 19, 2017). Accessed Nov. 7, 2022, at https://19january2017snapshot.epa.gov/pfas/what-are-pfcs-and-how-do-they-relate-and-polyfluoroalkyl-substances-pfass_.html. EPA noted that the acronym, PFCs, can also refer to perfluorocarbons that are distinct from PFAS or perfluorinated chemicals. Perfluorocarbons are not toxic, but they are a powerful and long-lasting greenhouse gas. Andrew B. Lindstrom et al. Polyfluorinated Compounds: Past, Present, and Future. Environmental Science & Technology (2011), 45, 7954-7961, 7954. Accessed Nov. 7, 2022, at https://pubs.acs.org/doi/pdf/10.1021/es2011622.

[20] David Andrews and Bill Walker. Environmental Working Group. Poisoned Legacy (April 2015), at 6. Accessed Nov. 7, 2022, at https://www.ewg.org/research/poisoned-legacy. Nathaniel Rich. The Lawyer Who Became Dupont's Worst Nightmare. New York Times Magazine (Jan. 6, 2016). Accessed Nov. 7, 2022, at https://www.nytimes.com/2016/01/10/magazine/the-lawyer-who-became-duponts-worst-nightmare.html?searchResultPosition=1. Andrew B. Lindstrom et al. Polyfluorinated Compounds: Past, Present, and Future. Environmental Science & Technology (2011), 45, 7954-7961, 7954, 7956. Accessed Nov. 7, 2022, at https://pubs.acs.org/doi/pdf/10.1021/es2011622.

[21] David Andrews and Bill Walker. Environmental Working Group. Poisoned Legacy (April 2015), at 6. Accessed Nov. 7, 2022, at https://www.ewg.org/research/poisoned-legacy. Andrew B. Lindstrom et al. Polyfluorinated Compounds: Past, Present, and Future. Environmental Science & Technology (2011), 45, 7954-7961, 7954. Accessed Nov. 7, 2022, at https://pubs.acs.org/doi/pdf/10.1021/es2011622.

[22] U.S. Environmental Protection Agency. PFAS Strategic Roadmap: EPA's Commitments to Action 2021-2024 (Oct. 2021), at 23. Accessed Nov. 7, 2022, at https://www.epa.gov/system/files/documents/2021-10/pfas-roadmap_final-508.pdf.

[23] David Andrews and Bill Walker. Environmental Working Group. Poisoned Legacy (April 2015), at 6-8. Accessed Nov. 7, 2022, at https://www.ewg.org/research/poisoned-legacy. Nathaniel Rich. The Lawyer Who Became Dupont's Worst Nightmare. New York Times Magazine (Jan. 6, 2016). Accessed Nov. 7, 2022, at https://www.nytimes.com/2016/01/10/magazine/the-lawyer-who-became-duponts-worst-nightmare.html?searchResultPosition=1.

[24] David Andrews and Bill Walker. Environmental Working Group. Poisoned Legacy (April 2015), at 8, 23. Accessed Nov. 7, 2022, at https://www.ewg.org/research/poisoned-legacy. Nathaniel Rich. The Lawyer Who Became Dupont's Worst Nightmare. New York Times Magazine (Jan. 6, 2016). Accessed Nov. 7, 2022, at https://www.nytimes.com/2016/01/10/magazine/the-lawyer-who-became-duponts-worst-nightmare.html?searchResultPosition=1.

[25] Nathaniel Rich. The Lawyer Who Became Dupont's Worst Nightmare. New York Times Magazine (Jan. 6, 2016). Accessed Nov. 7, 2022, at https://www.nytimes.com/2016/01/10/magazine/the-lawyer-who-became-duponts-worst-nightmare.html?searchResultPosition=1. Cleveland Clinic. Thyroid Disease. Accessed Sept. 5, 2022, at https://my.clevelandclinic.org/health/diseases/8541-thyroid-disease. Graham J. Burton et al. Pre-eclampsia: Pathophysiology and Clinical Implications. National Library of Medicine. PubMed.gov (July 15, 2019). Accessed Nov. 7, 2022, at https://pubmed.ncbi.nlm.nih.gov/31307997/. Mahesh Gajendran et al. A Comprehensive Review and Update on Ulcerative Colitis (March 2, 2019). National Library of Medicine. PubMed.gov. Accessed Sept. 5, 2022, at https://pubmed.ncbi.nlm.nih.gov/30837080/.

[26] U.S. Environmental Protection Agency. Our Current Understanding of the Human Health and Environmental Risks of PFAS. Accessed Mar. 6, 2023, at https://www.epa.gov/pfas/our-current-understanding-human-health-and-environmental-risks-pfas.

[27] Agency for Toxic Substances and Disease Registry. What are the health effects of PFAS? Accessed Mar. 6, 2023, at https://www.atsdr.cdc.gov/pfas/health-effects/index.html.

[28] Andrew B. Lindstrom et al. Polyfluorinated Compounds: Past, Present, and Future. Environmental Science & Technology (2011), 45, 7954-7961, 7956. Accessed Sept. 5, 2022, at https://pubs.acs.org/doi/pdf/10.1021/es2011622. Shantal Riley. Toxic Synthetic "Forever Chemicals" are in Our Water and on Our Plates. NOVA (PBS) (Nov. 2, 2020). Accessed Sept. 5, 2022, at https://www.pbs.org/wgbh/nova/article/pfas-synthetic-chemicals-water-toxic/. Oklahoma State University. Professor's Startup Turns Research into Real-World Solutions. News and Information (Oct. 3, 2018). Accessed Sept. 5, 2022, at https://news.okstate.edu/articles/arts-sciences/2018/professors-startup-turns-research-into-real-world-solutions.html.

[29] U.S. Environmental Protection Agency. EPA's Per- and Polyfluoroalkyl Action Plan (Feb. 2019) at 13. Accessed Nov. 7, 2022, at https://www.epa.gov/sites/default/files/2019-02/documents/pfas_action_plan_021319_508compliant_1.pdf.

[30] U.S. Environmental Protection Agency. Technical Fact Sheet: Drinking Water Health Advisoriesfor Four PFAS (PFOA, PFOS, GenX chemicals, and PFBS). June 2022, at 2. Accessed Nov. 7, 2022, at https://www.epa.gov/system/files/documents/2022-06/technical-factsheet-four-PFAS.pdf.

[31] U.S. Environmental Protection Agency. Technical Fact Sheet: Drinking Water Health Advisories for Four PFAS (PFOA, PFOS, GenX chemicals, and PFBS). June 2022, at 2. Accessed Nov. 7, 2022, at https://www.epa.gov/system/files/documents/2022-06/technical-factsheet-four-PFAS.pdf.

[32] U.S. Environmental Protection Agency. Technical Fact Sheet: Drinking Water Health Advisories for Four PFAS (PFOA, PFOS, GenX chemicals, and PFBS). June 2022, at 4. Accessed Nov. 7, 2022, at https://www.epa.gov/system/files/documents/2022-06/technical-factsheet-four-PFAS.pdf.

[33] U.S. Environmental Protection Agency. Technical Fact Sheet: Drinking Water Health Advisories for Four PFAS (PFOA, PFOS, GenX chemicals, and PFBS). June 2022, at 4. Accessed Nov. 7, 2022, at https://www.epa.gov/system/files/documents/2022-06/technical-factsheet-four-PFAS.pdf.

[34] U.S. Environmental Protection Agency. Technical Fact Sheet: Drinking Water Health Advisories for Four PFAS (PFOA, PFOS, GenX chemicals, and PFBS). June 2022, at 4. Accessed Nov. 7, 2022, at https://www.epa.gov/system/files/documents/2022-06/technical-factsheet-four-PFAS.pdf.

[35] Electronic mail communication with Ashley Greene, U.S. Environmental Protection Agency (March 21,2023).

[36] Washington State Department of Health. 2022 EPA Health Advisory Levels for Four PFAS (Oct. 21, 2022). Accessed Mar. 24, 2023, at https://doh.wa.gov/sites/default/files/2022-10/331-702.pdf.

[37] PSR calculated the amount of PFOA that could contaminate the total storage capacity of the Elephant Butte Reservoir using the following data: EPA's interim health advisory level for PFOA is 0.004 parts per trillion. U.S. Environmental Protection Agency. Technical Fact Sheet: Drinking Water Health Advisories for Four PFAS (PFOA, PFOS, GenX chemicals, and PFBS). June 2022, at 4. Accessed Sept. 20, 2022, at https://www.epa.gov/system/files/documents/2022-06/technical-factsheet-four-PFAS.pdf. Parts per trillion refers to milligrams per one million liters of water. U.S. Environmental Protection Agency. Environmental Science and Technology Briefs for Citizens. Center for Hazardous Substance Research. Understanding Units of Measurement. Accessed Sept. 20, 2022, at https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.files/fileid/14285. One measuring cup contains approximately 237 milliliters. Exploratorium. Cooking Equivalents and Measures. Accessed September 20, 2022, at https://www.exploratorium.edu/food/measurements. The density of PFOA is 1.8 grams per milliliter. National Institutes of Health. National Library of Medicine. National Center for Biotechnology Information. PubChem. Perfluorooctanoic Acid. Density. Accessed September 20, 2022, at https://pubchem.ncbi.nlm.nih.gov/compound/Perfluorooctanoic-acid. Therefore, the mass of one measuring cup of PFOA is 426.6 grams or 426,600 milligrams. This mass of PFOA is 106,650,000 times greater than 0.004 milligrams (EPA's interim health advisory level per million liters). In order to dilute the mass of the PFOA in an equivalent volume of water, we multiplied 106,650,000 by 1,000,000. The result is 106,650,000,000,000 liters of water. There are 3.785 liters of water per gallon. U.S. Environmental Protection Agency. EPA. ExpoBox Unit Conversion Table. Accessed September 20, 2022, at https://www.epa.gov/expobox/epa-expobox-unit-conversion-table. Therefore, 106,650,000,000,000 liters of water is equal to a bit more than 28 trillion gallons of water – the amount of water that could be contaminated to EPA's interim health advisory level by one measuring cup of PFOA. There are 16 tablespoons in a measuring cup. Irma S. Rombauer et al. The Joy of Cooking (2019), at 1036. Therefore, a tablespoon of PFOA could contaminate 1.75 trillion gallons of water, a volume more than twice the total storage capacity of the Elephant Butte Reservoir, 720 billion gallons. Bureau of Reclamation. Elephant Butte Reservoir (reporting that the Elephant Butte Dam and Reservoir "...can store 2,210,298 acre-feet of water to provide irrigation and year-round power generation"). Accessed Dec. 15, 2022, at https://www.usbr.gov/projects/index.php?id=94. Texas A&M University. Texas Water. FAQs (reporting that "An acre-foot is enough water to cover 1 acre of land to a depth of 1 foot; it is 325,851 gallons of water." Accessed Dec. 15, 2022, at https://texaswater.tamu.edu/faqs.html#:~:text=Texans%20use%20about%2016.5%20million,is%20325%2C851%20gallons%20of%20water. Multiplying 2,210,298 acre feet by 325,851 gallons per acre foot results in approximately 720 billion gallons of water, the total storage capacity of the Elephant Butte Reservoir.

[38] Bureau of Reclamation. Elephant Butte Dam. Accessed Dec. 15, 2022, at https://www.usbr.gov/projects/index.php?id=94.

[39] New Mexico Tourism Department. New Mexico True. Elephant Butte Lake. Accessed Dec. 15, 2022, at https://www.newmexico.org/things-to-do/outdoor-adventures/lakes-rivers/.

[40] Algernon D'Ammassa. Despite Monsoons, Elephant Butte Irrigation District Forecasts a Dry 2023. Las Cruces Sun-News (Oct. 14, 2022). Accessed Dec. 15, 2022, at https://www.lcsun-news.com/story/news/local/water/2022/10/14/elephant-butte-irrigation-district-forecasts-dry-2023-despite-monsoons/69563603007/.

[41] U.S. Environmental Protection Agency. EPA's Proposal to Limit PFAS in Drinking Water (March 2023). Fact Sheet. Accessed Mar. 15, 2023, at https://www.epa.gov/system/files/documents/2023-03/Fact%20Sheet_PFAS_NPWDR_Final_3.14.23.pdf.

[42] Electronic mail communication with Linda Birnbaum (Mar. 10, 2023).

[43] Electronic mail communication with Zacariah Hildenbrand (Mar. 14, 2023).

[44] Electronic mail communication with Kevin Schug (Mar. 14, 2023).

[45] Electronic mail communication with Wilma Subra (Mar. 14, 2023).

[46] New Mexico PBS. Groundwater War: New Mexico's Toxic Threat. Accessed Dec. 17, 2022, at https://www.newmexicopbs.org/productions/groundwater-war/2021/01/19/new-pfas-study-reveals-forever-pollutants-persisting-in-nms-waters/.

[47] Letter from Michelle Hunter, Chief Ground Water Quality Bureau, New Mexico Environment Department to Chris Segura, Chief Installation Support Section AFCEC/CZOW (Sept. 26, 2018), at 2. Accessed Feb. 28, 2023, at https://www.newmexicopbs.org/productions/groundwater-war/timeline/.

[48] Letter from Michelle Hunter, Chief Ground Water Quality Bureau, New Mexico Environment Department to Joseph Campo, Colonel, U.S. Air Force, Commander Holloman Air Force Base (Feb. 6, 2019). Accessed Feb. 28, 2023, at https://www.newmexicopbs.org/productions/groundwater-war/timeline/.

[49] New Mexico PBS. Groundwater War: New Mexico's Toxic Threat. Accessed Dec. 17, 2022, at https://www.newmexicopbs.org/productions/groundwater-war/2021/01/19/new-pfas-study-reveals-forever-pollutants-persisting-in-nms-waters/.

[50] Interstate Technology Regulatory Council. Aqueous Film-Forming Foam (Oct. 2018), at 3. Accessed Mar. 17, 2023, at https://pfas-1.itrcweb.org/fact_sheets_page/pfas-fact-sheet-afff-10-3-18.pdf.

[51] Theresa Davis. Cannon PFAS Destroyed Longtime Clovis Farmer's Dairy. Albuquerque Journal (May 28, 2022). Accessed Mar. 23, 2023, at https://www.abqjournal.com/2503560/cannon-pfas-destroyed-longtime-clovis-farmers-dairy.html.

[52] State of New Mexico Environment Department. News Release (Jan. 18, 2021). Accessed Dec. 17, 2021, at https://www.env.nm.gov/wp-content/uploads/2021/01/2021-01-18-Two-new-PFAS-efforts-underway.pdf.

[53] U.S. Geological Survey. PFAS Sampling Results – Groundwater. August 2020 – November 2021. Accessed Mar. 6, 2023, at https://cloud.env.nm.gov/water/resources/_translator.php/NoP4Wd1EyorPC~sl~BWz~sl~H2+PXdCQEKefUZ-Ma+xAlRrWuxlvdEEjyB6boWvUr+du0HuTYxK5+bF8GvKZQxfNvzloaRxrecez4uHXKYObY6qP8~sl~VqR3Qn6ZpJnP-DYOaGQRQa.pdf.

[54] New Mexico Environment Department. PFAS in New Mexico. Accessed Dec. 17, 2022, at https://www.env.nm.gov/pfas/.

[55] New Mexico Environment Department. PFAS in New Mexico. Accessed Dec. 17, 2022, at https://www.env.nm.gov/pfas/.

[56] U.S. Environmental Protection Agency. Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States. Washington, DC: Office of Research and Development; 2016, at ES-3, 4-8, 6-39. Accessed Sept. 5, 2022, at https://www.epa.gov/hfstudy.

[57] U.S. Environmental Protection Agency. Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States. Washington, DC: Office of Research and Development; 2016, at 8-25. Accessed Sept. 5, 2022, at https://www.epa.gov/hfstudy.

[58] U.S. Environmental Protection Agency. Saving Water in New Mexico (June 2013). Accessed Dec. 23, 2022, at https://www.epa.gov/sites/default/files/2017-02/documents/ws-ourwater-new-mexico-state-fact-sheet.pdf.

[59] Interstate Stream Commission. Pecos River Basin (2022). Accessed Dec. 23, 2022, at https://www.ose.state.nm.us/Basins/Pecos/isc_Pecos.php.

[60] U.S. Environmental Protection Agency. Getting up to Speed on Ground Water Contamination (August 2015), at C2. Accessed Dec. 23, 2022, at https://www.epa.gov/sites/default/files/2015-08/documents/mgwc-gwc1.pdf.

[61] U.S. Environmental Protection Agency. Getting up to Speed on Ground Water Contamination (August 2015), at C7. Accessed Dec. 23, 2022, at https://www.epa.gov/sites/default/files/2015-08/documents/mgwc-gwc1.pdf.

[62] Adrian Hedden. Study shows southeast New Mexico water gets scarcer in coming decades. Carlsbad Current-Argus (Oct. 22, 2021). Accessed Dec. 23, 2022, at https://www.currentargus.com/story/news/local/2021/10/22/study-shows-southeast-new-mexico-water-gets-scarcer-coming-decades/8521164002/.

[63] U.S. Environmental Protection Agency. Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States. Washington, DC: Office of Research and Development; 2016, at 3-18 through 3-22, 5-7, 5-8, 5-11, 5-16, 6-67. EPA Report # 600/R-16/236F. Accessed Sept. 7, 2022, at https://www.epa.gov/hfstudy. Genevieve A. Kahrilas et al. Biocides in Hydraulic Fracturing Fluids: A Critical Review of Their Usage, Mobility, Degradation, and Toxicity. Environ. Sci. Technol.201549116-32 (Nov. 26, 2014). Accessed Sept. 7, 2022, at https://pubs.acs.org/doi/10.1021/es503724k.

[64] U.S. Environmental Protection Agency. Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States. Washington, DC: Office of Research and Development; 2016, at 9-1. Accessed Sept. 7, 2022, at https://www.epa.gov/hfstudy.

[65] See, e.g., U.S. Environmental Protection Agency. Focus report for chemical with EPA case number P-06-0676. Washington, DC: New Chemicals Program; 2006 (on file with PSR).

[66] Colorado General Assembly. HB22-1348. Senate Amended 3rd Reading (May 11, 2022). Accessed Sept. 8, 2022, at https://leg.colorado.gov/sites/default/files/documents/2022A/bills/2022a_1348_rer.pdf.

[67] Ohio Department of Natural Resources, Division of Oil and Gas Resources Management, Oil and Gas Well Locator, Form 8(A) for well API Number 34-111-24285. Accessed Sept. 7, 2022, at https://gis.ohiodnr.gov/MapViewer/?config=oilgaswells.

[68] Concerned Health Professionals of New York and Physicians for Social Responsibility. Compendium of Scientific, Medical, and Media Findings Demonstrating Risks and Harms of Fracking (Unconventional Gas and Oil Extraction), Eighth Edition (2022). Accessed Sept. 8, 2022, at https://www.psr.org/blog/fracking-compendium-8th-edition-now-available/.

[69] Safer States et al. PFAS polymers pose serious health and environmental threats. Accessed Sept. 5, 2022, at https://www.nrdc.org/sites/default/files/pfas-polymer-fs.pdf.

[70] Rainer Lohmann et al. Are Fluoropolymers Really of Low Concern for Human and Environmental Health and Separate from Other PFAS? Environmental Science & Technology 2020, 54, 12820-12828, 12821-2. Accessed Sept. 5, 2022, at https://pubs.acs.org/doi/10.1021/acs.est.0c03244.

[71] Safer States et al. PFAS polymers pose serious health and environmental threats. Accessed Sept. 5, 2022, at https://www.nrdc.org/sites/default/files/pfas-polymer-fs.pdf.

[72] Rainer Lohmann et al. Are Fluoropolymers Really of Low Concern for Human and Environmental Health and Separate from Other PFAS? Environmental Science & Technology 2020, 54, 12820-12828, 12821-12822. Accessed Sept. 5, 2022, at https://pubs.acs.org/doi/10.1021/acs.est.0c03244.

[73] Rainer Lohmann et al. Are Fluoropolymers Really of Low Concern for Human and Environmental Health and Separate from Other PFAS? Environmental Science & Technology 2020, 54, 12820-12828, 12823. Accessed Sept. 5, 2022, at https://pubs.acs.org/doi/10.1021/acs.est.0c03244.

[74] Rainer Lohmann et al. Are Fluoropolymers Really of Low Concern for Human and Environmental Health and Separate from Other PFAS? Environmental Science & Technology 2020, 54, 12820-12828, 12823. Accessed Sept. 5, 2022, at https://pubs.acs.org/doi/10.1021/acs.est.0c03244.

[75] David A. Ellis et al. Thermolysis of fluoropolymers as a Potential Source of Halogenated Organic Acids in the Environment. Nature. Letters to Nature, Vol. 412 (July 19, 2001). Accessed Sept. 5, 2022, at https://pubmed.ncbi.nlm.nih.gov/11460160/.

[76] Rainer Lohmann et al. Are Fluoropolymers Really of Low Concern for Human and Environmental Health and Separate from Other PFAS? Environmental Science & Technology 2020, 54, 12820-12828, 12823-12824. Accessed Sept. 5, 2022, at https://pubs.acs.org/doi/10.1021/acs.est.0c03244.

[77] Schlumberger. The Defining Series: HPHT Wells (Mar. 10, 2016). Accessed Jan. 19, 2023 at https://www.slb.com/resource-library/oilfield-review/defining-series/defining-hpht. Schlumberger. Oilfield Review (Autumn 2008), at 46, 48. Accessed Nov. 5, 2022, at https://www.slb.com/-/media/files/oilfield-review/high-pressure-high-temperature.

[78] Electronic mail communication with Ian Cousins, professor, Department of Environmental Science, Stockholm University (Oct. 15, 2021).

[79] Joe Cruz. Administrative Bureau Chief. New Mexico Oil Conservation Division. Freedom of Information Act response to questions submitted by Dusty Horwitt (Jan. 19, 2023) (on file with PSR), at 3.

[80] Electronic mail from representative of New Mexico Oil Conservation Division to Dusty Horwitt (Jan. 19, 2023) (on file with PSR).

[81] Safer States et al. PFAS polymers pose serious health and environmental threats. Accessed Sept. 5, 2022, at https://www.nrdc.org/sites/default/files/pfas-polymer-fs.pdf.

[82] See, e.g., FracFocus. Find a Well. Well with API Number 30-015-42927 fracked by XTO Energy/ExxonMobil between June 7, 2018 and June 21, 2018.

[83] U.S. Environmental Protection Agency. Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States. Washington, DC: Office of Research and Development; 2016, at 5-5, 5-6, 5-8. Accessed Sept. 5, 2022, at https://www.epa.gov/hfstudy.

[84] The total weight figures reflect the sum of all records for which PSR found enough information to calculate a chemical's weight.

[85] Fortune. ExxonMobil. Accessed Sept. 8, 2022, at https://fortune.com/company/exxon-mobil/.

[86] Adrian Hedden. Devon Energy merges with WPX Energy in $12 billion deal focused on Permian Basin oil. Carlsbad Current-Argus (Sept. 30, 2020). Accessed Mar. 16, 2023, at https://www.currentargus.com/story/news/local/2020/09/30/devon-energy-wpx-deal-permian-basin-oil-gas-new-mexico/5868139002/.

[87] Adrian Hedden. Smaller 'independent' oil and gas producers leading Permian Basin growth, study says. Carlsbad Current-Argus (Dec. 3, 2021). Accessed Mar. 16, 2021, at https://www.currentargus.com/story/news/local/2021/12/03/study-smaller-independent-oil-and-gas-producers-leading-permian-basin/8726072002/.

[88] Lisa Dunlap. Major Permian Basin operators use 'green' technologies. Roswell Daily Record (Sept. 24, 2022). Accessed Mar. 16, 2023, at https://www.rdrnews. com/major-permian-basin-operators-use-green-technologies/article_736b61ca-35d5-11ed-ba0f-af78d7b24f8b.html.

[89] U.S. Environmental Protection Agency. Master List of PFAS Substances. Poly(oxy-1,2-ethanediyl), .alpha.-hydro-.omega.-hydroxy-, ether with .alpha.-fluoro-.omega.-(2-hydroxyethyl) poly(difluoromethyl. CAS number 65545-80-4. Accessed Nov. 9, 2022, at https://comptox.epa.gov/dashboard/chemical/details/DTXSID6049727.

[90] See, e.g., FracFocus. Find a Well. Well with API Number 30-025-42386 located in Lea County fracked by EOG Resources, Inc. between April 27, 2015 and May 8, 2015. Fracked between May 5, 2015 and May 7. 2015. Accessed Nov. 10, 2022, at https://fracfocusdata.org/DisclosureSearch/Search.aspx.

[91] See, e.g., FracFocus. Find a Well. Well with API Number 30-025-42386 located in Lea County fracked by EOG Resources, Inc. between April 27, 2015 and May 8, 2015. Fracked between May 5, 2015 and May 7. 2015. Accessed Nov. 10, 2022, at Find a Well | FracFocus Chemical Disclosure Registry (fracfocusdata.org) https://fracfocusdata.org/DisclosureSearch/Search.aspx.

[92] National Library of Medicine. ChemIDplus. CAS number 65545-80-4. Accessed Nov. 11, 2022, at https://chem.nlm.nih.gov/chemidplus/rn/65545-80-4.

[93] MilliporeSigma. Safety Data Sheet for Zonyl® FSO-100, a substance with CAS number 65545-80-4. Accessed Nov. 11, 2022, at https://www.sigmaaldrich.com/US/en/sds/aldrich/421456.

[94] ChemPoint. ZONAL® TO CAPSTONE® FLUOROSURFACTANT & REPELLENT TRANSITION GUIDE. Accessed Nov. 11, 2022, at https://go.chempoint.com/zonyl-capstone.

[95] N.M. Admin. Code 19.15.16.19.16 and its predecessor at N.M. Reg. Volume XXIII, Number 3 (Feb. 15, 2012), at 68. Accessed Dec. 20, 2022, at https://www.srca.nm.gov/nmac-home/new-mexico-register/.

[96] N.M. Admin. Code 19.15.16.19.16 (B)(2).

[97] ee, e.g., FracFocus. Find a Well. Well with API Number 30-025-42577 located in Lea County fracked by XTO Energy/Exxon Mobil between Sept. 1, 2015 and Sept. 3, 2015. Accessed April 6, 2023, at https://fracfocusdata.org/DisclosureSearch/Search.aspx.

[98] FFracFocus. Find a Well. Well with API Number 30-015-45990 located in Eddy County fracked by Chevron USA Inc. between August 7, 2021 and Sept. 5, 2021. Accessed April 6, 2023, at https://fracfocusdata.org/DisclosureSearch/Search.aspx.

[99] U.S. Environmental Protection Agency. Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States. Washington, DC: Office of Research and Development; 2016, at 3-14, 3-15, 10-14. Accessed Sept. 5, 2022, at https://www.epa.gov/hfstudy.

[100] Juliane Glüge et al. An Overview of the Uses of Per- and Polyfluoroalkyl Substances (PFAS) – Electronic Supplementary Information 1. Environmental Science: Processes and Impacts (Oct. 30, 2020) at 50-51. Accessed Sept. 7, 2022, at https://pubs.rsc.org/en/content/articlelanding/2020/em/d0em00291g#!divAbstract.

[101] See, e.g., New Mexico Energy, Minerals and Environment Department. Oil Conservation Division. Approval and Conditions associated with Application for Permit to Drill or Reenter for Well with API Number 30-045-35542 (Aug. 11, 2014). Accessed Mar. 5, 2023, at https://ocdimage.emnrd.nm.gov/imaging/Filestore/Aztec/WF/257117/30045355420000_1_ WF.pdf.

[102] Schlumberger. Oilfield Glossary. Mud. Accessed Mar. 5, 2023, at https://glossary.slb.com/en/terms/m/mud.

[103] Oklahoma State University Extension. An Introduction to the Land Application of Drilling Mud in Oklahoma. Accessed Mar. 5, 2023, at https://extension.okstate.edu/fact-sheets/an-introduction-to-the-land-application-of-drilling-mud-in-oklahoma.html.

[104] PSR calculated the estimated maximum amounts of trade secret chemicals used in each well in New Mexico primarily by using disclosures by well operators for each well listed in FracFocus. We then aggregated the maximum amounts for each well to calculate county-by-county and state-wide totals. To illustrate the

methodology, we will use as an example the figures from XTO Energy/ExxonMobil's well number 35-019-26303 fractured in Carter County, Oklahoma in 2019. We estimated the total mass of the hydraulic fracking fluid used in each well in pounds by multiplying the gallons of water listed as being used as the base fluid for the fracking fluid (223,650 in this case) by 8.33, the number of pounds in a gallon of water as listed in a table of the weights of various solvents published by the U.S. Environmental Protection Agency. See U.S. Environmental Protection Agency. Conversion from Gallons to Pounds of Common Solvents. Accessed Jan. 12, 2022, at https://www.epa.gov/p2/pollution-prevention-tools-and-calculators. That quantity of water in the XTO Energy/ExxonMobil example weighs approximately 1,863,005 pounds. We then calculated the total mass of the fracking fluid by multiplying the mass of the water in pounds by 100 and dividing that product by the listed maximum percent concentration of water in the fracking fluid (78.31797). The estimated total maximum mass of the fracking fluid in the example is 2,378,770 pounds. Next, we multiplied the listed maximum concentration in percent by mass of the potential PFAS chemical in the fracking fluid (0.00074) by the total estimated mass of the fluid. The result was an estimated maximum of 17.6 pounds of potential PFAS used to fracture the well. PSR included in our analysis of trade secret chemicals those chemicals in Open-FF whose specific identities were explicitly labeled "proprietary," "trade secret," or "confidential business information" in place of a CAS number. PSR did not include as trade secrets additional unidentified chemicals for which the CAS number in Open-FF is blank.

[105] U.S. Environmental Protection Agency. Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States. Washington, DC: Office of Research and Development; 2016, at 5-19. Accessed Sept. 5, 2022, at https://www.epa.gov/hfstudy.

[106] U.S. Environmental Protection Agency. Criteria for Biodegradability Claims on Products Registered under FIFRA. Accessed Mar. 30, 2021, at https://www.epa.gov/pesticide-labels/criteria-biodegradability-claims-products-registered-under-fifra.

[107] Robert C. Buck et al. Perfluoroalkyl and Polyfluoroalkyl Substances in the Environment: Terminology, Classification, and Origins. Integrated Environmental Assessment and Management — Volume 7, Number 4—pp. 513–541, 517. Accessed Sept. 7, 2022, at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3214619/pdf/ieam0007-0513.pdf.

[108] Robert C. Buck et al. Perfluoroalkyl and Polyfluoroalkyl Substances in the Environment: Terminology Classification, and Origins. Integrated Environmental Assessment and Management (2011) Volume 7, Number 4—pp. 513–541, 522. Accessed Sept. 7, 2022, at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3214619/pdf/ieam0007-0513.pdf.

[109] U.S. Environmental Protection Agency. Master List of PFAS Substances. 2-(Perfluorooctyl)ethanol. CAS number 678-39-7. Accessed Mar. 23, 2023, at https://comptox.epa.gov/dashboard/chemical/details/DTXSID7029904?list=PFASMASTER.

[110] Nicholas J. Herkert. Characterization of Per- and Polyfluorinated Alkyl Substances Present in Commercial Anti-fog Products and Their In Vitro Adipogenic Activity. Environmental Science & Technology (2022), 56, 1162-1173. Accessed Mar. 23, 2023, at https://pubs.acs.org/doi/pdf/10.1021/acs.est.1c06990.

[111] Robert C. Buck et al. Perfluoroalkyl and Polyfluoroalkyl Substances in the Environment: Terminology, Classification, and Origins. Integrated Environmental (Oct. 2011); 7(4): 513–541, at . Accessed Mar. 23, 2023, at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3214619/.

[112] Electronic mail communication with Zacariah Hildenbrand, PhD, Research Professor Chemistry and Biochemistry, University of Texas El Paso (Mar. 14, 2023). Electronic mail communication with Kevin Schug. Shimadzu Distinguished Professor of Analytical Chemistry, University of Texas at Arlington (Mar. 14, 2023).

[113] Electronic mail communication with Linda Birnbaum (Mar. 14, 2023). Electronic mail communication with Wilma Subra (Mar. 14, 2023).

[114] Juliane Glüge et al. An Overview of the Uses of Per- and Polyfluoroalkyl Substances (PFAS) – Electronic Supplementary Information 1. Environmental Science: Processes and Impacts (Oct. 30, 2020) at 50-51, 53. Accessed online Sept. 7, 2022, at https://pubs.rsc.org/en/content/articlelanding/2020/em/d0em00291g#!divAbstract.

[115] Peter M. Murphy and Tracy Hewat. Fluorosurfactants in Enhanced Oil Recovery. The Open Petroleum Engineering Journal, 1. 58-61, 58 (2008). Accessed Sept. 7, 2022, at https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.858.5125&rep=rep1&type=pdf.

[116] Peter M. Murphy and Tracy Hewat. Fluorosurfactants in Enhanced Oil Recovery. The Open Petroleum Engineering Journal, 1. 58-61, 58 (2008). Accessed Sept. 7, 2022, at https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.858.5125&rep=rep1&type=pdf.

[117] PSR determined that a chemical was a surfactant if the chemical's ingredient name or purpose was listed in FracFocus as a surfactant.

[118] PSR calculated the estimated maximum amounts of trade secret chemicals used in each well in New Mexico primarily by using disclosures by well operators for each well listed in FracFocus. We then aggregated the maximum amounts for each well to calculate county-by-county and state-wide totals. To illustrate the

methodology, we will use as an example the figures from XTO Energy/ExxonMobil's well number 35-019-26303 fractured in Carter County, Oklahoma in 2019. We estimated the total mass of the fracking fluid used in each well in pounds by multiplying the gallons of water listed as being used as the base fluid for the fracking fluid (223,650 in this case) by 8.33, the number of pounds in a gallon of water as listed in a table of the weights of various solvents published by the U.S. Environmental Protection Agency. See U.S. Environmental Protection Agency. Conversion from Gallons to Pounds of Common Solvents. Accessed Sept. 9, 2022, at https://www.epa.gov/p2/pollution-prevention-tools-and-calculators. That quantity of water in the XTO Energy/ExxonMobil example weighs approximately 1,863,005 pounds. We then calculated the total mass of the fracking fluid by multiplying the mass of the water in pounds by 100 and dividing that product by the listed maximum percent concentration.

[119] Electronic mail communication with Zacariah Hildenbrand and Kevin Schug (April 21, 2021, October 10-11, 2022). Telephone interview with Zacariah Hildenbrand (April 30, 2021). For their publications, see, e.g., Zacariah L. Hildenbrand, et al. Temporal variation in groundwater quality in the Permian Basin of Texas, a region of increasing unconventional oil and gas development. Sci Total Environ 2016;562:906–13 (2016). Accessed June 2, 2021, at https://www. sciencedirect.com/science/article/abs/pii/S0048969716308476.

[120] Electronic mail communication with Wilma Subra (May 11, 2021).

[121] Telephone interview with Linda Birnbaum (Mar. 17, 2021).

[122] Electronic mail communication with Linda Birnbaum (Mar. 4, 2023).

[123] Telephone interview with Linda Birnbaum (March 17, 2021). Linda Birnbaum, PhD. University of North Carolina. Gillings School of Global Public Health. Accessed Oct. 13, 2022, at https://sph.unc.edu/adv_profile/linda-birnbaum-phd/.

[124] Telephone interview with Zac Hildenbrand (Mar. 6, 2023).

[125] Electronic mail communication with Wilma Subra (Mar. 6, 2023).

[126] Electronic mail communication with Kevin Schug (Feb. 24, 2023).

[127] See, e.g., FracFocus. Find a Well. Well with API Number 30-025-42577 located in Lea County fracked by XTO Energy/Exxon Mobil between Sept. 1, 2015 and Sept. 3, 2015.

[128] See, e.g., FracFocus. Find a Well. Well with API Number 30-025-42577 located in Lea County fracked by XTO Energy/Exxon Mobil between Sept. 1, 2015 and Sept. 3, 2015.

[129] Mike Soraghan and Pamela King. Oilfield Spills Down 17% Last Year. EnergyWire (July 27, 2017). Accessed Sept. 8, 2022, at https://www.eenews.net/articles/oil-field-spills-down-17-last-year/.

[130] Center for Western Priorities. 2021 Spills Tracker (March 30, 2022). Accessed Dec. 23, 2022, at https://westernpriorities.org/resource/2021-spills-tracker/.

[131] New Mexico Energy, Minerals and Natural Resources Department. Implementation of the Produced Water Act Frequently Asked Questions (FAQs) (January 2020), at 2. Accessed Dec. 23, 2022, at https://www.env.nm.gov/wp-content/uploads/sites/16/2020/03/2020-1-29-WPD-PW-FAQs-Vol-1.-English-FINAL_date-corrected.pdf.

[132] New Mexico Energy, Minerals and Natural Resources Department. Implementation of the Produced Water Act Frequently Asked Questions (FAQs) (January 2020), at 2. Accessed Dec. 23, 2022, at https://www.env.nm.gov/wp-content/uploads/sites/16/2020/03/2020-1-29-WPD-PW-FAQs-Vol-1.-English-FINAL_date-corrected.pdf

[133] OECD Environmental Health and Safety Publications. Series on Emission Scenario Documents No. 31. EMISSION SCENARIO DOCUMENT ON CHEMICALS USED IN OIL WELL PRODUCTION (Mar. 19, 2012), at 8, 35-37 (reporting that "The U.S. Environmental Protection Agency led this project…"). Accessed Dec. 23, 2022, at https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=env/jm/mono(2012)7&doclanguage=en.

[134] Soni Grant and Melissa Troutman. 2022 Oil & Gas Spills Overwhelm New Mexico (March 2023). Center for Biological Diversity & WildEarth Guardians. Accessed April 6, 2023, at https://wildearthguardians.org/press-releases/toxic-oil-and-gas-spills-overwhelm-new-mexico-regulatory-agencies/.

[135] LT Environmental Inc. Report of Final Sampling & Closure Request NEU #315 Release Response (prepared for Enduring Resources, LLC) (Dec. 13, 2019), at 2-1.

[136] New Mexico Energy Minerals and Natural Resources Department. Oil Conservation Division. Release Notification. Incident ID NCS-1905249442 (received by OCD Dec. 19, 2019), at 1 (on file with PSR).

[137] LT Environmental Inc. Report of Final Sampling & Closure Request NEU #315 Release Response (prepared for Enduring Resources, LLC) (Dec. 13, 2019), at 2-1, 3-2 (on file with PSR).

[138] New Mexico Bureau of Geology & Mineral Resources. What Decision Makers Should Know about Arroyos in New Mexico. Accessed Mar. 4, 2023, at https://geoinfo.nmt.edu/hazards/erosion/home.html.

[139] New Mexico Energy Minerals and Natural Resources Department. Oil Conservation Division. Release Notification. Incident ID NCS-1905249442 (received by OCD Dec. 19, 2019), at 3.

[140] Ronald F. Broadhead and Alex Rinehart. New Mexico Bureau of Geology and Mineral Resources. The Oil and Natural Gas Potential Of Sandoval County, New Mexico and it's (sic) Relationship to Groundwater: Supplementary Report (Revised) (Nov. 9, 2018), at 48. Accessed Mar. 4, 2023, at https://www.sandovalcountynm.gov/wp-content/uploads/2018/11/NMTechSupplementSandovalReportRevised.pdf.

[141] Kendra Chamberlain. WPX settles with family over produced water spill. NM Political Report (Jan. 7, 2021). Accessed Dec. 23, 2022, at https://nmpoliticalreport.com/2021/01/07/wpx-settles-with-family-over-produced-water-spill/.

[142] Kendra Chamberlain. 'It was raining on us': Family awoken by produced water pipe burst near Carlsbad. NM Political Report (Jan. 24, 2020). Accessed Dec. 23, 2022, at https://nmpoliticalreport.com/2021/01/07/wpx-settles-with-family-over-produced-water-spill/.

[143] Kendra Chamberlain. WPX settles with family over produced water spill. NM Political Report (Jan. 7, 2021). Accessed Dec. 23, 2022, at https://nmpoliticalreport.com/2021/01/07/wpx-settles-with-family-over-produced-water-spill/.

[144] New Mexico Environment Department. Oil Conservation Division. Natural Gas and Oil Production (Friday, Mar. 3, 2023) (reporting that oil and gas wells in New Mexico generated more than two billion barrels of produced water in 2022 or almost 85 billion gallons at 42 gallons per barrel). Accessed Mar. 6, 2023, at https://wwwapps.emnrd.nm.gov/ocd/ocdpermitting/Reporting/Production/ExpandedProductionInjectionSummaryReport.aspx.

[145] New Mexico Environment Department. Produced Water Management in New Mexico (2019). Accessed Dec. 23, 2022, at https://www.env.nm.gov/wp-content/uploads/sites/16/2019/10/Produced-Water-Public-Meeting-Presentation_ENGLISH_FINAL-191015.pdf.

[146] Melissa Troutman and Amy Mall. New Mexico Oil and Gas Waste Report. Earthworks (Oct. 2020), at 14. Accessed Dec. 23, 2022, at https://earthworks.org/wp-content/uploads/2021/09/NM-Waste-Report-2020-final2.pdf.

[147] Texas Department of Agriculture. Agricultural Land and Water Contamination from Injection Wells, Disposal Pits, and Abandoned Wells used in Oil and Gas Production (1985), at 5 (on file with PSR).

[148] U.S. General Accounting Office. Safeguards Are Not Preventing Contamination from Injected Oil and Gas Wastes (July 1989), at 19. Accessed Sept. 8, 2022, at https://www.gao.gov/assets/150/147952.pdf. U.S. Environmental Protection Agency. Report to Congress: Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy, Vol. 1 of 3 (Dec. 1987), at III-47 through 48. Accessed Sept. 8, 2022, at https://archive.epa.gov/epawaste/nonhaz/industrial/special/web/pdf/530sw88003a.pdf.

[149] Texas Department of Agriculture. Agricultural Land and Water Contamination from Injection Wells, Disposal Pits, and Abandoned Wells used in Oil and Gas Production (1985), at 9 (on file with PSR).

[150] Texas Department of Agriculture. Agricultural Land and Water Contamination from Injection Wells, Disposal Pits, and Abandoned Wells used in Oil and Gas Production (1985), at 11 (on file with PSR).

[151] Texas Department of Agriculture. Agricultural Land and Water Contamination from Injection Wells, Disposal Pits, and Abandoned Wells used in Oil and Gas Production (1985), at 7 (on file with PSR).

[152] U.S. General Accounting Office. Safeguards Are Not Preventing Contamination from Injected Oil and Gas Wastes (July 1989), at 20-21, 25. Accessed Sept. 8, 2022, at https://www.gao.gov/assets/150/147952.pdf.

[153] Office of the Governor, Michelle Lujan Grisham. New Mexico to Get $43.7 Million for Orphan Well Clean-up (Jan. 31, 2022). Accessed Dec. 23, 2022, at https://www.governor.state.nm.us/2022/01/31/new-mexico-to-get-43-7-million-for-orphan-well-clean-up/.

[154] Laura Paskus. New Mexico's "Fracking" Legacy. KUNM (July 11, 2012). Accessed Dec. 23, 2022, at https://www.kunm.org/local-news/2012-07-11/new-mexicos-fracking-legacy.

[155] N.M. Reg. Vol. XIX, No. 11 (June 16, 2008) 372-384. Accessed February 16, 2023, at https://www.srca.nm.gov/nmac/nmregister/pdf/xix11.pdf.

[156] N.M. Reg. Vol. XIX, No. 11 (June 16, 2008) 372-384, 374. Accessed February 16, 2023, at https://www.srca.nm.gov/nmac/nmregister/pdf/xix11.pdf.

[157] Melissa Troutman and Amy Mall. New Mexico Oil and Gas Waste Report. Earthworks (Oct. 2020), at 12. Accessed Dec. 23, 2022, at https://earthworks.org/wp-content/uploads/2021/09/NM-Waste-Report-2020-final2.pdf.

[158] N.M. Admin. Code 19.15.17.10 (A)(1).

[159] N.M. Reg. Vol. XIX, No. 11 (June 16, 2008) 372-384, 380-382 (N.M. Admin. Code 19.15.17.13 (F). Accessed February 16, 2023, at https://www.srca.nm.gov/nmac/nmregister/pdf/xix11.pdf.

[160] N.M. Admin. Code 19.15.17.13(D)(5)(referencing Table II of N.M. Admin. Code 19.15.17.13).

[161] Melissa Troutman and Amy Mall. New Mexico Oil and Gas Waste Report. Earthworks (Oct. 2020), at 12-13. Accessed Dec. 23, 2022, at https://earthworks.org/wp-content/uploads/2021/09/NM-Waste-Report-2020-final2.pdf.

[162] Melissa Troutman and Amy Mall. Wasted in the Lone Star State: The Impacts of Toxic Oil and Gas Waste in Texas. Earthworks (April 2021), at 6. Accessed Oct. 24, 2022, at https://earthworks.org/assets/uploads/2021/05/Wasted-in-TX-final-web.pdf

[163] Dusty Horwitt. Fracking with Forever Chemicals. Physicians for Social Responsibility (July 2021), at 15. Accessed Sept. 8, 2022, at https://www.psr.org/wp-content/uploads/2021/07/fracking-with-forever-chemicals.pdf. Telephone interview with David Brown (January 26, 2023).

[164] Isabel Koyama et al. New Mexico Wants it 'Both Ways,' Insisting on Environmental Regulations While Benefiting from Oil and Gas. Inside Climate News (Feb. 27, 2022). Accessed Dec. 24, 2022, at https://insideclimatenews.org/news/27022022/new-mexico-oil-gas-flaring-venting/.

[165] Rob Verger. What it Really Takes to Power Your Home for a Day. Popular Science (June 8, 2018). Accessed Dec. 24, 2022, at https://www.popsci.com/what-it-takes-to-power-home-for-day/.

[166] Kevin Crowley. Natural Gas Flaring is Set to Rebound in the Permian Basin. Bloomberg (Nov. 14, 2022). Accessed Dec. 24, 2022, at https://www.bloomberg.com/news/articles/2022-11-14/permian-flaring-to-rebound-even-as-market-endures-natural-gas-shortages.

[167] Kevin Crowley. Natural Gas Flaring is Set to Rebound in the Permian Basin. Bloomberg (Nov. 14, 2022). Accessed Dec. 24, 2022, at https://www.bloomberg.com/news/articles/2022-11-14/permian-flaring-to-rebound-even-as-market-endures-natural-gas-shortages.

[168] Isabel Koyama et al. New Mexico Wants it 'Both Ways,' Insisting on Environmental Regulations While Benefiting from Oil and Gas. Inside Climate News (Feb. 27, 2022). Accessed Dec. 24, 2022, at https://insideclimatenews.org/news/27022022/new-mexico-oil-gas-flaring-venting/.

[169] Isabel Koyama et al. New Mexico Wants it 'Both Ways,' Insisting on Environmental Regulations While Benefiting from Oil and Gas. Inside Climate News (Feb. 27, 2022). Accessed Dec. 24, 2022, at https://insideclimatenews.org/news/27022022/new-mexico-oil-gas-flaring-venting/.

[170] Electronic mail communication from Wilma Subra (Jan. 23, 2023).

[171] Nichola Groom and Valerie Volcovici. Texas repeatedly raises pollution limits for Cheniere LNG plant. Reuters (June 25, 2022). Accessed Mar. 23, 2023, https://www.reuters.com/business/environment/texas-repeatedly-raises-pollution-limits-cheniere-lng-plant-2022-06-24/.

[172] Natural Gas Weekly Update for Week Ending May 25, 2022. Accessed Mar. 5, 2023, at https://www.eia.gov/naturalgas/weekly/archivenew_ngwu/2022/05_26/.

[173] Eclampsia is different from pre-eclampsia. See U.S. Department of Health and Human Services. National Institutes of Health. Preeclampsia and Eclampsia. Accessed Oct. 23, 2022, at https://www.nichd.nih.gov/health/topics/preeclampsia.

[174] Mary D Willis et al., Associations between Residential Proximity to Oil and Gas Extraction and Hypertensive Conditions during Pregnancy: A Difference-in-Differences Analysis in Texas, 1996–2009. International Journal of Epidemiology (May 2022): vol. 51, no. 2. Accessed Oct. 23, 2022, at https://doi.org/10.1093/ije/dyab246.

[175] Lara Cushing et al. Flaring from Unconventional Oil and Gas Development and Birth Outcomes in the Eagle Ford Shale in South Texas. Environmental Health Perspectives (2020) 128(7):077003. Accessed Dec. 5, 2022, at https://doi.org/10.1289/.

[176] Mary Willis et al., Natural Gas Development, Flaring Practices and Paediatric Asthma Hospitalizations in Texas. International Journal of Epidemiology (2020): vol. 49, no. 6 (2021): 1883–96. Accessed Oct. 23, 2022, at https://doi.org/10.1093/ije/dyaa115.

[177] Lisa M. McKenzie et al. Congenital heart defects and intensity of oil and gas well site activities in early pregnancy. Environment International (2019) 132, 104949. Accessed Jan. 12, 2022, at https://www.sciencedirect.com/science/article/pii/S0160412019315429?via%3Dihub.

[178] Lisa M. McKenzie et al. Childhood hematologic cancer and residential proximity to oil and gas development. PLOS One (2017) 12(2): e0170423. Accessed Nov. 7, 2022, at https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0170423.

[179] Concerned Health Professionals of New York and Physicians for Social Responsibility. Compendium of Scientific, Medical, and Media Findings Demonstrating Risks and Harms of Fracking (Unconventional Gas and Oil Extraction), Eighth Edition (2022), at 54. Accessed Sept. 8, 2022, at https://www.psr.org/blog/fracking-compendium-8th-edition-now-available/.

[180] U.S. Centers for Disease Control. Infant Mortality. Accessed Sept. 8, 2022, at https://www.cdc.gov/reproductivehealth/maternalinfanthealth/infantmortality.htm.

[181] Office of the Attorney General, Commonwealth of Pennsylvania. Report 1 of the Forty-Third Statewide Investigating Grand Jury (June 25, 2020), at 12. Accessed Sept. 8, 2022, at https://www.attorneygeneral.gov/wp-content/uploads/2020/06/FINAL-fracking-report-w.responses-with-page-number-V2.pdf.

[182] Office of the Attorney General, Commonwealth of Pennsylvania. Report 1 of the Forty-Third Statewide Investigating Grand Jury (June 25, 2020), at 12. Accessed Sept. 8, 2022, at https://www.attorneygeneral.gov/wp-content/uploads/2020/06/FINAL-fracking-report-w.responses-with-page-number-V2.pdf.

[183] U.S. Department of Energy. Energy Information Administration. Natural Gas. Natural Gas Gross Withdrawals and Production. Dry Production, Annual-Million Cubic Feet. Accessed Sept. 8, 2022, at https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FPD_mmcf_a.htm.

[184] Office of the Attorney General, Commonwealth of Pennsylvania. Report 1 of the Forty-Third Statewide Investigating Grand Jury (June 25, 2020), at 4-5. Accessed Sept. 8, 2022, at https://www.attorneygeneral.gov/wp-content/uploads/2020/06/FINAL-fracking-report-w.responses-with-page-number-V2.pdf.

[185] Lara J. Cushing et al. Up in Smoke: Characterizing the Population Exposed to Flaring from Unconventional Oil and Gas Development in the Contiguous US. Environmental Research Letters (2021): 16 034032. Accessed Dec. 5, 2022, at https://doi.org/10.1088/1748-9326/abd3d4.

[186] Jill E. Johnston et al. Environmental Justice Dimensions of Oil and Gas Flaring in South Texas: Disproportionate Exposure among Hispanic Communities. Environmental Science & Technology (2020): 54, 10 6289–98. Accessed Oct. 23, 2022, at https://doi.org/10.1021/acs.est.0c00410.

[187] Jill E. Johnston, et al. Wastewater Disposal Wells, Fracking, and Environmental Injustice in Southern Texas. American Journal of Public Health (2016): 106, 550–56. Accessed Oct. 23, 2022, at https://doi.org/10.2105/AJPH.2015.303000.

[188] Bureau of Land Management. Farmington Mancos-Gallup Draft Resource Management Plan Amendment and Environmental Impact Statement, Vol. 1 (2020). At 3-219 to 3-220. Accessed Mar. 4, 2023, at https://drive.google.com/file/d/1nZ5feeEBkJkkQi7STDFxN7V4EZP3dV9B/view.

[189] David J. Tsosie and Herbert Benally. A Cultural, Spiritual and Health Impact Assessment Of Oil Drilling Operations in the Navajo Nation area of Counselor, Torreon and Ojo Encino Chapters (July 15, 2021), at 14. Accessed Mar. 6, 2023, at https://nmhep.org/wp-content/uploads/FINAL-HIA-KBHIS-06-52-2021-00-copy1.pdf.

[190] David J. Tsosie and Herbert Benally. A Cultural, Spiritual and Health Impact Assessment Of Oil Drilling Operations in the Navajo Nation area of Counselor, Torreon and Ojo Encino Chapters (July 15, 2021), at 26-27. Accessed Mar. 6, 2023, at https://nmhep.org/wp-content/uploads/FINAL-HIA-KBHIS-06-52-2021-00-copy1.pdf.

[191] David J. Tsosie and Herbert Benally. A Cultural, Spiritual and Health Impact Assessment Of Oil Drilling Operations in the Navajo Nation area of Counselor, Torreon and Ojo Encino Chapters (July 15, 2021), at 44. Accessed Mar. 6, 2023, at https://nmhep.org/wp-content/uploads/FINAL-HIA-KBHIS-06-52-2021-00-copy1.pdf.

[192] Ian Urbina. Pressure Limits Efforts to Police Drilling for Gas. New York Times (Mar. 3, 2011). Accessed Sept. 8, 2022, at https://www.nytimes.com/2011/03/04/us/04gas.html?ref=us. Related sidebar, Lax Rules for the Natural Gas Industry, accessed Sept. 8, 2022, at https://archive.nytimes.com/www.nytimes.com/interactive/2011/03/03/us/20110303-natural-gas-timeline.html.

[193] Michael Janofsky. Dupont to Pay $16.5 Million for Unreported Risks. New York Times (Dec. 15, 2005). Accessed Sept. 8, 2022, at https://www.nytimes.com/2005/12/15/politics/dupont-to-pay-165-million-for-unreported-risks.html. The Lawyer Who Became Dupont's Worst Nightmare. New York Times Magazine (Jan. 6, 2016). Accessed Sept. 8, 2022, at https://www.nytimes.com/2016/01/10/magazine/the-lawyer-who-became-duponts-worst-nightmare.html?searchResultPosition=1 (reporting that Dupont's settlement payment amounted to less than two percent of Dupont's profits from PFOA that year and the company was not required to admit liability).

[194] U.S. Environmental Protection Agency. Fact Sheet: 2010/2015 PFOA Stewardship Program. Accessed Jan. 12, 2022, at https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/fact-sheet-20102015-pfoa-stewardship-program. U.S. Environmental Protection Agency. 2010/15 PFOA Stewardship Program. Guidance on Reporting Emissions and Product Content (October 2006). Accessed Jan. 12, 2022, at https://www.epa.gov/sites/default/files/2015-10/documents/pfoaguidance.pdf. Nathaniel Rich. The Lawyer Who Became DuPont's Worst Nightmare. New York Times Magazine (Jan. 6, 2016).

Accessed Sept. 7, 2022, at https://www.nytimes.com/2016/01/10/magazine/the-lawyer-who-became-duponts-worst-nightmare.html?searchResultPosition=1.

[195] U.S. Environmental Protection Agency. Fact Sheet: 2010/2015 PFOA Stewardship Program. Accessed Sept. 9, 2022, at https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/fact-sheet-20102015-pfoa-stewardship-program.

[196] U.S. Environmental Protection Agency. Fact Sheet: 2010/2015 PFOA Stewardship Program. Accessed Nov. 7, 2022, at https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/fact-sheet-20102015-pfoa-stewardship-program.

[197] Rainer Lohmann et al. Are Fluoropolymers Really of Low Concern for Human and Environmental Health and Separate from Other PFAS? Environmental Science & Technology 2020, 54, 12820-12828, 12821-12822. Accessed Jan. 12, 2022, at https://pubs.acs.org/doi/10.1021/acs.est.0c03244.

[198] U.S. Environmental Protection Agency. Fact Sheet: 2010/2015 PFOA Stewardship Program. Accessed Nov. 7, 2022, at https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/fact-sheet-20102015-pfoa-stewardship-program.

[199] Earthjustice. EPA's Secret Chemical Problem, Unveiled. Accessed Sept. 9, 2022, at https://earthjustice.org/sites/default/files/files/20200317_comms_pc_tsca_english_final.pdf. Sharon Lerner. EPA Continues to Approve Toxic PFAS Chemicals Despite Widespread Contamination. The Intercept (Oct. 25, 2018). Accessed Sept. 9, 2022, at https://theintercept.com/2018/10/25/epa-pfoa-pfas-pfos-chemicals/.

[200] Arlene Blum et al. The Madrid Statement on Poly- and Perfluoroalkyl Substances (PFASs). Environmental Health Perspectives (May 1, 2015), Vol. 123, No. 5. Accessed Sept. 9, 2022, at https://ehp.niehs.nih.gov/doi/10.1289/ehp.1509934.

[201] U.S. Environmental Protection Agency. PFAS Strategic Roadmap: EPA's Commitments to Action 2021-2024 (Oct. 2021), at 7. Accessed Sept. 5, 2022, at https://www.epa.gov/system/files/documents/2021-10/pfas-roadmap_final-508.pdf.

[202] Letter from U.S. Rep. Jared Huffman et al. to U.S. Environmental Protection Agency Administrator Michael S. Regan (Oct. 27, 2021). Accessed Sept. 9, 2022, at https://huffman.house.gov/media-center/press-releases/huffman-calls-on-epa-to-protect-public-from-chemical-hazards-created-by-hydraulic-fracturing.

[203] Physicians for Social Responsibility. Comments submitted to the U.S. Environmental Protection Agency in reference to Docket Identification (ID) Number EPA-HQ-OPPT-2020-0549 (Sept. 27, 2021).

[204] U.S. Environmental Protection Agency. Technical Fact Sheet: Drinking Water Health Advisoriesfor Four PFAS (PFOA, PFOS, GenX chemicals, and PFBS). June 2022, at 2. Accessed Sept. 9, 2022, at https://www.epa.gov/system/files/documents/2022-06/technical-factsheet-four-PFAS.pdf.

[205] U.S. Environmental Protection Agency. EPA Proposes Designating Certain PFAS Chemicals as Hazardous Substances Under Superfund to Protect People's Health (Aug. 26, 2022). Accessed Dec. 24, 2022, at https://www.epa.gov/newsreleases/epa-proposes-designating-certain-pfas-chemicals-hazardous-substances-under-superfund.

[206] U.S. Environmental Protection Agency. Superfund Liability (July 25, 2022). Accessed Dec. 24, 2022, at https://www.epa.gov/enforcement/superfund-liability.

[207] Interstate Technology Regulatory Council. Fact Sheets: PFAS Water and Soil Regulatory and Guidance Values Table Excel File. Water Table. Accessed Mar. 17, 2023, at https://pfas-1.itrcweb.org/.

[208] Michigan Department of Environment, Great Lakes, and Energy. Michigan Adopts Strict PFAS in Drinking Water Standards. News Release (July 22, 2020). Accessed Jan. 12, 2022, at https://www.michigan.gov/egle/0,9429,7-135--534660--,00.html

[209] Tim Buckland. Toxic GenX: Defining Parts Per Trillion. Wilmington (N.C.) Star News (August 18, 2017). Accessed Jan. 12, 2022, at https://www.starnewsonline.com/news/20170818/what-does-140-parts-per-trillion-look-like.

[210] U.S. Department of Energy. Energy Information Administration. Petroleum & other Liquids. Crude Oil Production. Annual – Thousand Barrels. Accessed Sept. 9, 2022, at https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm.

[211] Cal. Public Resources. § 3160 (j)(2)(A) (providing that "Notwithstanding any other law or regulation, none of the following information shall be protected as a trade secret…The identities of the chemical constituents of additives [in well stimulation treatment fluids], including CAS identification numbers."

[212] U.S. Department of Energy. Secretary of Energy Advisory Board Task Force Report on FracFocus 2.0 (Mar. 28, 2014). Accessed Sept. 9, 2022, at https://www.energy.gov/sites/default/files/2014/04/f14/20140328_SEAB_TF_FracFocus2_Report_Final.pdf. U.S. Department of Energy. Secretary of Energy Advisory Board Task Force Report on FracFocus 2.0 (Mar. 28, 2014). Accessed Sept 9, 2022, at https://www.energy.gov/sites/default/files/2014/04/f14/20140328_SEAB_TF_FracFocus2_Report_Final.pdf.

[213] Colorado General Assembly. HB22-1348. Senate Amended 3rd Reading (May 11, 2022). Accessed Sept. 9, 2022, at https://leg.colorado.gov/sites/default/files/documents/2022A/bills/2022a_1348_rer.pdf.

[214] U.S. Department of Energy. Secretary of Energy Advisory Board Task Force Report on FracFocus 2.0 (Mar. 28, 2014). Accessed Sept. 9, 2022, at https://www.energy.gov/sites/default/files/2014/04/f14/20140328_SEAB_TF_FracFocus2_Report_Final.pdf.

[215] U.S. Department of Energy. Secretary of Energy Advisory Board Task Force Report on FracFocus 2.0 (Mar. 28, 2014). Accessed Sept. 9, 2022, at https://www.energy.gov/sites/default/files/2014/04/f14/20140328_SEAB_TF_FracFocus2_Report_Final.pdf.

[216] Cal. Public Resources. § 3160 (j)(5-7).

[217] Cal. Public Resources § 3160 (j)(2).

[218] Cal. Public Resources. § 3160(d)(6).

[219] W. Va. Code §§ 22-6A-7(e)(5), 22-6A-10(b).

[220] Wyoming Admin. Code Ch. 3 § 45(a).

[221] New Mexico Admin. Code 19.15.16.19

[222] New Mexico Admin. Code 19.15.16.19(B)(1).

[223] Kate Konschnik et al. Legal Fractures in Chemical Disclosure Laws: why the voluntary chemical disclosure registry FracFocus fails as a regulatory compliance tool. Harvard Law School, Environmental Law Program Policy Initiative; 2013, at 5. See http://blogs.harvard.edu/environmentallawprogram/files/2013/04/4-23-2013-LEGALFRACTURES.pdf. 29 CFR § 1910.1200; 2018.

[224] For example, in 2014, four attorneys with years of experience litigating oil and gas-related cases in Pennsylvania filed a petition with the state Commonwealth Court suggesting manufacturers often withhold chemical identities from other companies in the supply chain. See Petitioners' pleading filed in Robinson Twp. v. Commonwealth, Docket No. 284 MD 2012 (June 9, 2014), at 13 FN5 (on file with PSR). The attorneys provided as support a record filed in a separate case by well operator Range Resources in which Range suggested that it was relying on Material Safety Data Sheets from manufacturers to reply to a request for the chemicals used to fracture or stimulate its wells. "The MSDS are often useful for developing some understanding of what is in a particular chemical or product," Range wrote. "However, they vary widely in terms of usefulness. Some manufacturers include very little information about the actual components of a particular product. As a result, Range is currently in the process of seeking additional information from manufacturers that have failed to provide enough information about their products in the MSDS." See Kiskadden v. Department of Environmental Protection v. Range Resources – Appalachia, LLC. Docket No. 2011-149-R. Permittee Range Resources – Appalachia, LLC's Amended Responses and Objections to Appellant's Request for Production of Documents and Request for Admission. Filed with Commonwealth of Pennsylvania Environmental Hearing Board (April 24, 2013) (on file with PSR).

[225] Colorado House Bill 22-1348(2)(f) (enacted June 8, 2022). Accessed Sept. 8, 2022, at https://leg.colorado.gov/sites/default/files/2022a_1348_signed.pdf

[226] Colorado House Bill 22-1348(2)(A)(II) (enacted June 8, 2022). Accessed Sept. 8, 2022, at https://leg.colorado.gov/sites/default/files/2022a_1348_signed.pdf.

[227] Julianne Glüge et al. Information Requirements under the Essential-Use Concept: PFAS Case Studies. Environmental Science & Technology (Oct. 5, 2021). Accessed Sept 9, 2022, at https://pubs.acs.org/doi/10.1021/acs.est.1c03732.

[228] Letter from Michelle Lujan Grisham to EPA Administrator Michael Regan regarding the listing of PFAS as hazardous under the federal Resource Conservation and Recovery Act (June 23, 2021). Accessed Jan. 19, 2023, at https://www.epa.gov/system/files/documents/2021-10/508compliant_ezd5442262_2021-06-23-governor-letter-to-epa-for-pfas-petition.pdf-incoming-document.pdf.

[229] U.S. Environmental Protection Agency. Resource Conservation and Recovery Act (RCRA) Overview. Accessed Jan. 20, 2023, at https://www.epa.gov/rcra/resource-conservation-and-recovery-act-rcra-overview.

[230] Letter from Michelle Lujan Grisham to EPA Administrator Michael Regan regarding the listing of PFAS as hazardous under the federal Resource Conservation and Recovery Act (June 23, 2021), at 1-2. Accessed Jan. 19, 2023, at https://www.epa.gov/system/files/documents/2021-10/508compliant_ezd5442262_2021-06-23-governor-letter-to-epa-for-pfas-petition.pdf-incoming-document.pdf.

[231] Letter from EPA Administrator Michael S. Regan to New Mexico Governor Michelle Lujan Grisham (Oct. 26, 2021). Accessed Jan. 20, 2023, at https://www.epa.gov/system/files/documents/2021-10/oct_2021_response_to_nm_governor_pfas_petition_corrected.pdf.

[232] U.S. Environmental Protection Agency. Regulatory Determination for Oil and Gas and Geothermal Exploration, Development and Production Wastes. 53 FR 25447 (July 6, 1988). Accessed Jan. 20, 2023, at https://archive.epa.gov/epawaste/nonhaz/industrial/special/web/pdf/og88wp.pdf.

[233] N.M. Admin. Code 19.15.36.13(F)(1)(referencing form C-138). Accessed Feb. 20, 2023, at https://www.srca.nm.gov/parts/title19/19.015.0036.html. Form C-138 accessed Feb. 20, 2023, at https://www.emnrd.nm.gov/ocd/wp-content/uploads/sites/6/2022-1011-C-138-with-updated-instructions.pdf.

[234] S. 3392 (signed by governor Aug. 3, 2020). Accessed Jan. 20, 2023, at https://www.nysenate.gov/legislation/bills/2019/s3392.

[235] New York State Senator Rachel May. Legislature Closes Decade Long Loophole on Treatment of Hazardous Fracking Waste. News Release (July 22, 2020). Accessed Jan. 20, 2023, at https://www.nysenate.gov/newsroom/press-releases/rachel-may/legislature-closes-decade-long-loophole-treatment-hazardous.

[236] Oil Conservation Division Permitting. Accessed Feb. 20, 2023, at https://wwwapps.emnrd.nm.gov/ocd/ocdpermitting/OperatorData/PermitStatusResults.aspx?Type=HFFD.

[237] N.M. Reg. Volume XXIII, Number 3 (Feb. 15, 2012), at 68 (N.M. Admin. Code 19.15.16.19.16) (requiring fracking chemical disclosure to the state) and N.M. Reg. Volume XXVIII, Issue 18 (Sept. 26, 2017), at 757-758 (N. M. Admin. Code 19.15.16.19) (requiring fracking chemical disclosure to FracFocus. Accessed Dec. 20, 2022, at https://www.srca.nm.gov/nmac-home/new-mexico-register/.

[238] FracFocus. About. Accessed Sept. 5, 2022, at https://www.fracfocus.org/index.php?p=about.

[239] Groundwater Protection Council. Overview. Accessed Sept. 5, 2022, at https://www.gwpc.org/about-us/overview/.

[240] Gary Allison (2021) Open-FF: Transforming the FracFocus Disclosure Data into a Usable Resource [Source Code]. Accessed Oct. 26, 2022, at https://doi.org/10.24433/CO.1058811.v15. PSR accessed Open-FF data set downloaded from FracFocus on Sept. 29, 2022.

[241] Gary Allison (2021) Open-FF: Transforming the FracFocus Disclosure Data into a Usable Resource [Source Code]. Accessed Oct. 26, 2022, at https://doi.org/10.24433/CO.1058811.v15.

[242] N.M. Admin. Code § 19.15.16.19(B).

[243] See, e.g., FracFocus. Find a Well. Well with API Number 30-015-45600 fracked by Chevron USA Inc. Between June 18, 2022 and July 5, 2022, in Eddy County.

[244] N.M. Reg. Volume XXIII, Number 3 (Feb. 15, 2012), at 68 (N.M. Admin. Code 19.15.16.19.16) Accessed Dec. 20, 2022, at https://www.srca.nm.gov/nmac-home/new-mexico-register/.

[245] N.M. Admin. Code § 19.15.16.19(B)(2).

PSR 1985 NOBEL PEACE PRIZE PHYSICIANS FOR SOCIAL RESPONSIBILITY
U.S. AFFILIATE OF INTERNATIONAL PHYSICIANS FOR THE PREVENTION OF NUCLEAR WAR

1111 14th Street NW, #700
Washington, DC 20005
202 667 4260
www.psr.org
psrnatl@psr.org

@PSRenvironment and @PSRnuclear
/psrnational

Technical/Regulatory Guidance

Per- and Polyfluoroalkyl Substances (PFAS)

IMPORTANT: This guidance document was developed for use on the web. Please review the following disclaimers before using the PDF version of this web-based document.

- **Web-Based formatting may not be optimal when using this document as a PDF.**
- **This is a read-only PDF conversion of the web-based document. Hyperlinks throughout this file have been disabled.**
- **Glossary terms are not hyperlinked.**

September 2023

Prepared By

The Interstate Technology & Regulatory Council (ITRC)

Per- and Polyfluoroalkyl Substances Team

NMOGA Exhibit D5

Table of Contents

About ITRC

The Interstate Technology and Regulatory Council (ITRC) is a state-led coalition working to reduce barriers to the use of innovative environmental technologies and approaches so that compliance costs are reduced and cleanup efficacy is maximized. ITRC produces documents and training that broaden and deepen technical knowledge and expedite quality regulatory decision making while protecting human health and the environment. With private and public sector members from all 50 states and the District of Columbia, ITRC truly provides a national perspective. More information on ITRC is available at www.itrcweb.org.

ITRC is a program of the Environmental Research Institute of the States (ERIS), a 501(c)(3) organization incorporated in the District of Columbia and managed by the Environmental Council of the States (ECOS). ECOS is the national, nonprofit, nonpartisan association representing the state and territorial environmental commissioners. Its mission is to serve as a champion for states; to provide a clearinghouse of information for state environmental commissioners; to promote coordination in environmental management; and to articulate state positions on environmental issues to Congress, federal agencies, and the public.

Disclaimer

This material was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof and no official endorsement should be inferred.

The information provided in documents, training curricula, and other print or electronic materials created by the Interstate Technology and Regulatory Council (“ITRC” and such materials are referred to as “ITRC Materials”) is intended as a general reference to help regulators and others develop a consistent approach to their evaluation, regulatory approval, and deployment of environmental technologies. The information in ITRC Materials was formulated to be reliable and accurate. However, the information is provided “as is” and use of this information is at the users’ own risk.

ITRC Materials do not necessarily address all applicable health and safety risks and precautions with respect to particular materials, conditions, or procedures in specific applications of any technology. Consequently, ITRC recommends consulting applicable standards, laws, regulations, suppliers of materials, and material safety data sheets for information concerning safety and health risks and precautions and compliance with then-applicable laws and regulations. ITRC, ERIS and ECOS shall not be liable in the event of any conflict between information in ITRC Materials and such laws, regulations, and/or other ordinances. The content in ITRC Materials may be revised or withdrawn at any time without prior notice.

ITRC, ERIS, and ECOS make no representations or warranties, express or implied, with respect to information in ITRC Materials and specifically disclaim all warranties to the fullest extent permitted by law (including, but not limited to, merchantability or fitness for a particular purpose). ITRC, ERIS, and ECOS will not accept liability for damages of any kind that result from acting upon or using this information.

ITRC, ERIS, and ECOS do not endorse or recommend the use of specific technology or technology provider through ITRC Materials. Reference to technologies, products, or services offered by other parties does not constitute a guarantee by ITRC, ERIS, and ECOS of the quality or value of those technologies, products, or services. Information in ITRC Materials is for general reference only; it should not be construed as definitive guidance for any specific site and is not a substitute for consultation with qualified professional advisors.

PFAS HOME

This Interstate Technology and Regulatory Council (ITRC) online document includes the resources that the ITRC PFAS Team has developed since it began work in 2017.

- PFAS Fact Sheets
- PFAS Technical and Regulatory Guidance Document
    - External Data Tables
- Training Resources
    - Quick Explainer Videos
    - Longer PFAS Training Module Videos
    - Archived Roundtable Sessions
    - PFAS Training Page

You can reach this PFAS Home page from any of the pages on this web site with the Home button at the top of screen.

PFAS Technical and Regulatory Guidance Document

The last full update of this document was September 2023.

⇐ **ONLINE DOCUMENT**: On this web page, use the Table of Contents shown in the left-hand navigation column to select a specific section of interest

- Full Guidance Document PDF (to be posted)
- Find the References, Glossary and Acronyms with these links or at the footer of the web

External Data Tables

In many of the sections of the PFAS Guidance Document the team has developed tables that provide additional data and information to support the topics in the sections. These tables are linked here, along with identity of the section with which the table is associated.

- Fact Sheets: PFAS Water and Soil Regulatory and Guidance Values Table Excel File
- Fact Sheets: PFAS Air Criteria Table Excel File
- Section 2: Figure 2-5 Expanded PFAS Family Tree PDF
- Section 2: USEPA Analytes List-PFAS Classifications PDF
- Section 3: AFFF Characteristics Excel File

- Section 3: AFFF Transition to F3 Case Studies Excel File
- Section 4: Physical and Chemical Properties Table 4-1 Excel File
- Section 5: Aquatic Organisms BCF-BAF Table 5-1 Excel file
- Section 5: Plants BCF-BAF Table 5-2 Excel File
- Section 8: PFAS Regulatory Programs Summary Excel File
- Section 11: Analytical Methods Excel File
- Section 11: PFAS Data Usability Table PDF
- Section 12: Table 12-1 Treatment Methods Table Excel File
- Section 12: Integrated Water Treatment Flow Chart PDF
- Section 14: Risk Communication Social Factors Vision Board PDF
- Section 15: Water Treatment Case Studies Excel File
- Section 17.1: Table 17-1 A-C for Air PDF
- Section 17.1: Table 17-2 A-C for Soil, Sediments, and Biosolids PDF
- Section 17.2: Table 17-8 Toxicological Effects Excel File

Archived External Tables and Sections

These resources are no longer being updated.

- Fact Sheets: Basis for PFOA and PFOS Regulatory Values in Drinking Water Table Excel File
- Section 6: Media-Specific Occurrence PDF
- Section 7.2: Ecotoxicology Data Summary Excel File
- Section 12: Table 12-1 Liquids Treatment Methods Table PDF
- Section 12: Table 12-2 Solids Treatment Methods Table PDF
- Section 17-1: Additional Information for Media-Specific Occurrence PDF

Training Resources

Quick Explainer Videos

The PFAS Team developed brief explainer videos to accompany the fact sheets. The following links will redirect you to ITRC's PFAS Explainer Videos on YouTube:

- ITRC PFAS Team Introduction
- PFAS Naming Conventions
- PFAS History and Use
- PFAS Fate and Transport
- PFAS Remediation
- PFAS Lab Analytical Methods
- Aqueous Film Forming Foam

Longer PFAS Training Module Videos

The PFAS Team developed training module videos to accompany this Technical and Regulatory Document. The following links will redirect you to ITRC's PFAS Training Module Videos on Youtube:

- PFAS introduction
- Naming Conventions and Physical and Chemical Properties
- Production, Uses, Sources and Site Characterization
- Sampling and Analysis
- Fate and Transport
- Human and Ecological Effects
- Risk Assessment and Regulations
- Treatment Technologies
- Aqueous Film-Forming Foam
- Risk Communication

PFAS Training on Clu-In

- PFAS Introductory Training

Archived Round Table Sessions

The PFAS Roundtable Sessions offered a unique opportunity to interact directly with PFAS experts from around the country on a different group of topics for each session. Each Roundtable is archived for On Demand listening and includes a Q&A Digest of all questions asked for the event, including those that were not addressed during the live class.

- Roundtable Session 1 – Naming Conventions, Sampling and Analytical Techniques, and History and Uses of PFAS (July 2020)
    - Roundtable Session 1 Digest
- Roundtable Session 2 – Physical & Chemical Properties, Site Characterization, Fate and Transport (October 2020)
    - Roundtable Session 2 Digest
- Roundtable Session 3 – AFFF and Treatment Technologies (April 6, 2021)
    - Roundtable Session 3 Digest
- Roundtable Session 4 – Human and Ecological Health Effects, Site Risk Assessment, Regulations, Risk Communication and Stakeholder Perspectives
    - Roundtable Session 4 Digest

Published by the Interstate Technology & Regulatory Council, September 2023

PFAS Fact Sheets

This page includes links for the ITRC PFAS fact sheets. The fact sheets are available as PDF files. Several tables of supporting information are published separately so that they can be updated periodically by ITRC. The fact sheet user should visit this page to access the current versions of the files.

The references list and an acronyms list are available on the website.

- Naming Conventions (updated September 2023)
- Regulations (updated September 2023)
    - PFAS Water and Soil Values Table Excel file– (updated August 2023)
        - The Water Table includes the available PFAS water values established by the USEPA, each pertinent state, or country (Australia, Canada and Western European countries)
        - The Soil Table includes the available PFAS soil values established by the USEPA, each pertinent state, or country (Australia, Canada and Western European countries)
    - PFAS Air Criteria Table Excel File – (updated September 2023)
- History and Use (updated September 2023)
- Fate and Transport and Physical and Chemical Properties (updated September 2023)
    - Physical and Chemical Properties Table 4-1 for select PFAS Excel file (updated July 2023)
- Sampling Precautions and Laboratory Analytical Methods (updated September 2023)
- Site Characterization and Media-Specific Occurrence (updated September 2023)
- Treatment Technologies and Methods (updated September 2023)
- Aqueous Film-Forming Foam (updated September 2023)
- Human and Ecological Health Effects and Risk Assessment (updated September 2023)
- Risk Communication (updated September 2023)
- Stakeholder Perspectives (updated September 2023)
- Surface Water Quality (updated September 2023)
- Biosolids and Per- and Polyfluoroalkyl Substances (updated September 2023)

PFAS Fact Sheets en Español

ITRC’s most popular PFAS Fact Sheets are now available in Spanish! Click the links below to view the PDF files.

- Naming Conventions (Published August 2022)
- Regulations (Published August 2022)
- History and Use (Published July 2022)
- Fate and Transport and Physical and Chemical Properties (Published July 2022)
- Sampling Precautions and Laboratory Analytical Methods (Published July 2022)
- Site Characterization and Media-Specific Occurrence (Published July 2022)
- Treatment Technologies and Methods (Published April 2022)
- Aqueous Film-Forming Foam (Published April 2022)
- Human and Ecological Health Effects and Risk Assessment (Published April 2022)
- Risk Communication (Published April 2022)
- Stakeholder Perspectives (Published April 2022)

PFAS Fact Sheets em Português

ITRC’s most popular PFAS Fact Sheets are now available in Portuguese! Click the links below to view the PDF files.

- Naming Conventions (Published January 2023)
- Regulations (Published January 2023)
- History and Use (Published January 2023)

- Fate and Transport and Physical and Chemical Properties (Published January 2023)
- Sampling Precautions and Laboratory Analytical Methods (Published January 2023)

PFAS Explainer Videos

The PFAS Team developed brief explainer videos to accompany the fact sheets. The following links will redirect you to ITRC's PFAS Explainer Videos on YouTube:

- ITRC PFAS Team Introduction
- PFAS Naming Conventions
- PFAS History and Use
- PFAS Fate and Transport
- PFAS Remediation
- PFAS Lab Analytical Methods
- Aqueous Film Forming Foam

Updated September 2023

1 Introduction

A PFAS introduction Video is available.

Per- and polyfluoroalkyl substances (PFAS) constitute a large family of fluorinated chemicals, exceeding several thousand that might be in commercial use or the environment, that vary widely in their chemical and physical properties. The number of PFAS and their uses have expanded over the years. It has been estimated that the PFAS family may include more than 12,000 chemical substances (USEPA 2020). A recent inventory of PFAS identified more than 4,700 PFAS with Chemical Abstracts Service (CAS) Registry Numbers that could have been, or may be, on the global market (OECD 2021), although the uses of each of these PFAS may not be known (KEMI 2015). More information is included in Section 2.

The persistence and mobility of some PFAS, combined with decades of widespread use in industrial processes, certain types of firefighting foams, and consumer products, have resulted in their being present in environmental media at trace levels across the globe. PFAS have relatively recently come to the attention of investigators and the public in large part due to the fact that until the early 2000s analytical methods to detect low levels of PFAS in the environment were available only in a few select research institutions. It was not until the early 2010s that these methods to detect a limited number of PFAS became widely available and had detection limits in water low enough to be commensurate with levels of potential human health effects. Toxicological studies have raised concerns regarding the bioaccumulative nature and potential health concerns of some PFAS (Section 7). As a result, our understanding of PFAS and the risks they may pose is rapidly evolving.

Broadly speaking, PFAS are characterized as having carbon atoms linked to each other and bonded to fluorine atoms, by which the fluorination imparts properties to the molecule. The carbons may be partially fluorinated (polyfluorinated) or fully fluorinated (perfluorinated). Modifying characteristics, such as addition of a functional group, other substitutions (for example, chlorine), and partial fluorination, are described in Section 2.2 along with evolving definitions of PFAS.

This guidance document is designed specifically to support state and federal environmental staff, as well as others (including stakeholders, project managers, and decision makers), to gain a working knowledge of the current state of PFAS science and practice. Developed by a team of over 500 environmental practitioners drawn from state and federal government, academia, industry, environmental consulting, and public interest groups, it also provides a summary of the current understanding of all aspects of PFAS from a broad perspective. While every effort was made to keep the information accessible to a wide audience, it is assumed the reader has some basic technical background in chemistry, environmental sciences, and risk assessment. The document addresses the following questions:

Questions	**Document Sections**
What are PFAS?	• Naming Conventions and Use • Chemistry, Terminology, and Acronyms • PFAS Uses and Products • PFAS Releases to the Environment • Firefighting foams (AFFF)
How do they behave in the environment?	• Physical and Chemical Properties • Environmental Fate and Transport Processes • Media-Specific Occurrence
Why are we concerned about PFAS?	• Human and Ecological Health Effects • Basis of Regulations • Site Risk Assessment • Surface Water Quality
How do we evaluate PFAS in the environment?	• Site Characterization • Sampling and Analysis • Case Studies

Questions	**Document Sections**
How do we remediate PFAS?	• Treatment Technologies
What are the major concerns of communities and Tribes and how do we share what we know about PFAS?	• Stakeholder Perspectives • Risk Communication

The thousands of chemicals that make up the large family known as PFAS can be divided into two major classes: nonpolymers and polymers. This document focuses primarily on those nonpolymer PFAS that, to date, are most commonly detected in the environment, particularly the highly persistent perfluoroalkyl acids (PFAAs), some of the better-known replacements for phased-out long-chain PFAAs, and some of the precursor chemicals—PFAS that can break down to form PFAAs. These precursors include *poly*fluorinated alkyl substances and a subset of polymer PFAS known as side-chain fluorinated polymers (Washington et al. 2018). Many polymer PFAS, especially certain high–molecular weight fluoropolymers, are insoluble in the environment and not bioavailable, and therefore less of a concern to human and ecological health (Henry et al. 2018), so are not discussed in detail in this document. As this paragraph illustrates, it is important to be clear about which PFAS is being discussed and what its particular physical and chemical properties are.

The physical and chemical properties that make some PFAS persistent and mobile in the environment also make them particularly challenging to analyze and remediate. Analytical methods sensitive enough to detect environmentally relevant concentrations became widely available in the early 2010s. Although analyte lists continue to expand, and methods continue to be developed, currently available methods still only allow identification of a small fraction of the thousands of PFAS that have reportedly been created and used since the 1950s. As existing analytical methods improve and new, nontargeted analyses become commercially available, it is likely that additional PFAS and new release sites will be identified.

Concerns have been raised regarding human health and ecological risks associated with certain PFAS. These are based on widespread detections of some PFAS in humans and wildlife, evidence that certain PFAS bioaccumulate in individuals and bioconcentrate in the food chain, and studies reporting multiple toxicological effects in animals and potential health effects in humans. However, risk assessment of PFAS is hampered by the unique physical and chemical properties of many PFAS, which result in uncertainty in identifying sources and quantifying source area mass, complex fate and transport in the environment, poorly understood biological and chemical transformation pathways, and unique bioaccumulation processes. Moreover, the widespread presence of some PFAS in environmental media and the many potential PFAS sources also complicate interpretation of site data. Data evaluation methods to help distinguish between site-specific anthropogenic “background” PFAS, PFAS that are site-related, and PFAS from another nearby source are still being developed.

As with other emerging contaminants, our evolving understanding of PFAS and the volume of scientific studies makes it difficult for most environmental practitioners to stay current with the critical information about these chemicals. Meanwhile, public concern about PFAS has created pressure on state and federal agencies to take action, resulting in evolving regulatory approaches and regulatory standards, screening values, and guidance values. Our understanding of PFAS will continue to improve as more scientific research is completed and published.

Updated September 2023

2 PFAS Chemistry and Naming Conventions, History and Use of PFAS, and Sources of PFAS Releases to the Environment

The PFAS Team developed a **Naming Conventions and Physical and Chemical Properties** training video and a **Production, Uses, Sources and Site Characterization** training video with content related to this section.

This section provides a basis for the discussion of PFAS in the environment by presenting foundational information about its discovery, commercial use, health and environmental awareness, chemistry, and terminology.

In 1938, Roy J. Plunkett at the DuPont Company's Jackson Laboratory discovered polytetrafluoroethylene (PTFE) while conducting commercial experiments with chlorofluorocarbon refrigerants (Science History Institute 2017).

Since the 1950s, many products commonly used by consumers and industry have been manufactured with or from PFAS, as the unique physical and chemical properties of PFAS impart oil, water, stain, and soil repellency, chemical and thermal stability, and/or friction reduction to a range of products. These products have applications in many industries, including the aerospace, semiconductor, medical, automotive, construction, electronics, and aviation industries, as well as in consumer products (such as carpets, clothing, furniture, outdoor equipment, food packaging), and firefighting applications (3M Company 1999; Buck et al. 2011; KEMI 2015; USEPA 2017).

The number of PFAS and their uses have expanded over the years. It has been estimated that the PFAS family may include more than 12,000 chemical substances (USEPA 2020). A recent inventory of PFAS identified more than 4,700 PFAS with Chemical Abstracts Service (CAS) Registry Numbers that could have been, or may be, on the global market (OECD 2021), although the uses of each of these PFAS may not be known (KEMI 2015). Publicly available health and toxicity studies are limited to only a small fraction of PFAS, and modern commercially available analytical technologies typically identify and quantify only about 50–60 PFAS, but these lists are increasing. An industry survey, reported in Buck et al. (2021), noted that only 256 of the 4,700 PFAS with CAS Registry Numbers are commercially relevant, with others of lesser environmental significance but potentially still occurring in the environment. However, it should be noted that (1) the results of this survey reflect responses from only three major global producers of PFAS that use the fluorotelomerization manufacturing process, (2) the results of this survey do not include any producers that use the electrochemical fluorination manufacturing process; and (3) some of the information provided by the participating companies was flagged as confidential business information.

Scientific, regulatory, and public concerns have emerged about potential health and environmental impacts associated with chemical production, product manufacture and use, and disposal of PFAS-containing wastes. These concerns have led to efforts to reduce the use of or replace certain PFAS, such as certain long-chain perfluoroalkyl carboxylates, long-chain perfluoroalkane sulfonates and their precursors, including two widely produced, commonly encountered, and most studied compounds: perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) (USEPA 2016; WA DER 2017). Refer to the Water and Soil Regulatory and Guidance Values Table Excel file, the PFAS Regulatory Programs Summary Excel file, and Section 8 for updated regulatory actions, and Section 13 for stakeholder perspective.

PFAS have followed a similar pattern of emergence and awareness exhibited by many other anthropogenic environmental contaminants. Figure 2-1 provides a general timeline of PFAS emergence and awareness that includes categories of 1) synthesis/development, 2) commercial production, 3) health concerns, 4) environmental detection, and 5) reduction/alternatives. There may be evidence of some activities occurring before or after dates provided in this timeline; the intent of the figure is to capture the years of significance for each category.

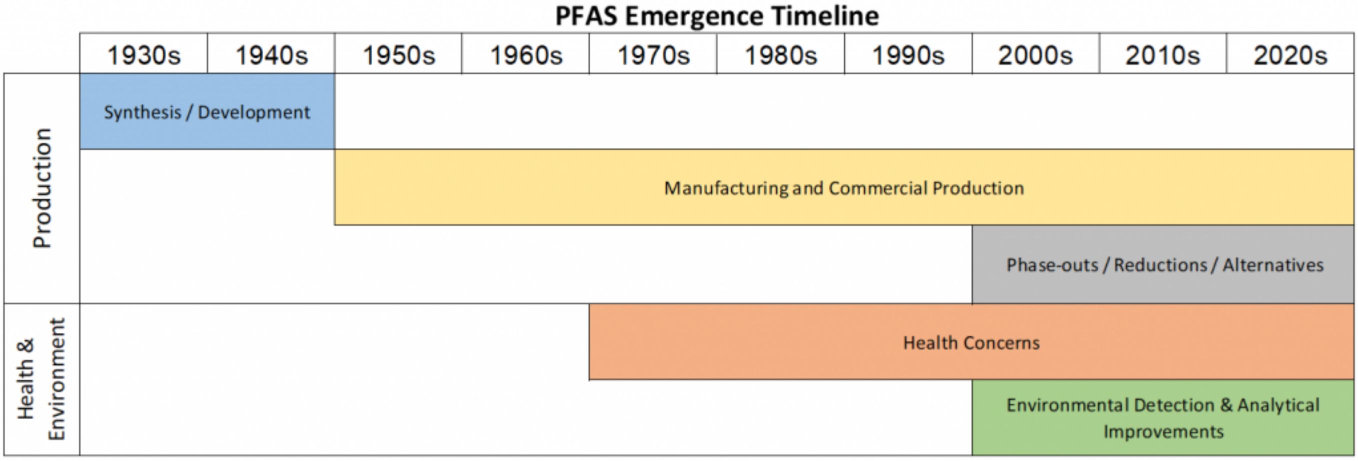


Figure 2-1. General timeline of PFAS emergence and awareness.

Graphic provides general indication of PFAS emergence and awareness by decade. Specific activities and events are described in more detail within this chapter. "Reductions/alternatives" refers to reduction in production/use and includes other PFAS that have replaced legacy chemistry.

Source: J. Hale, Kleinfelder. Used with permission.

The objective of this section is to lay a foundation for identifying potential PFAS sources in the environment.

Section Number	**Topic**
2.1	Environmental Significance
2.2	Chemistry, Terminology, and Acronyms
2.3	Emerging Health and Environmental Concerns
2.4	PFAS Reductions and Alternative PFAS Formulations
2.5	PFAS Uses and Products
2.6	PFAS Releases to the Environment

Updated September 2023.

2.1 Environmental Significance

PFAS have been and still are widely used, but not all types and uses of PFAS result in the same level of environmental impact and exposure. When considering potential environmental impacts from PFAS, it can be useful to be as specific as possible not only about the particular PFAS involved, but also where and how they are released to the environment. For example, a stable, insoluble fluoropolymer such as PTFE may pose little environmental/ecological or health risk once it is in a product. However, potentially significant environmental releases of other PFAS historically or currently used in the manufacturing process (for example, perfluoroalkyl acids [PFAAs], GenX, ADONA) have occurred. Such considerations may help to focus investigation resources on major sources. Addressing PFAS in a holistic manner is an emerging subject (Cousins et al. 2019) that may be helpful considering data are not available, for example, on the environmental fate and transport, environmental toxicity, or bioavailability, for all individual PFAS chemicals.

Figure 2-2 illustrates a conceptual PFAS lifecycle beginning at PFAS synthesis (raw materials). These raw materials are then used in a variety of manufacturing processes and industrial/commercial applications to create commercial and consumer products that contain or are treated with PFAS. Throughout this life cycle, variable types and amounts of PFAS may be released to the environment from manufacturing waste streams, fugitive emissions, spills, disposal of PFAS-containing or -treated materials, and general wear and tear of consumer products. Sometimes the intended use of the PFAS product (for example, firefighting foams) requires direct release to the environment. PFAS from a host of sources also may be conveyed through and aggregated in wastewater treatment plant effluent and sludges, creating sources of releases to the environment. The volume, concentration, and mixture of PFAS released to the environment varies based on the source (process, material, or product), release mechanism(s), and environmental controls employed throughout this life cycle. Exposure to PFAS may occur as (1) direct interaction with the manufacturing process, (2) professional or intensive use of PFAS-containing materials, (3) use of or contact with commercial and consumer products containing PFAS, or (4) exposure (human or ecological) to environmental media that have been impacted by PFAS. The relative significance of these exposures will also vary widely.

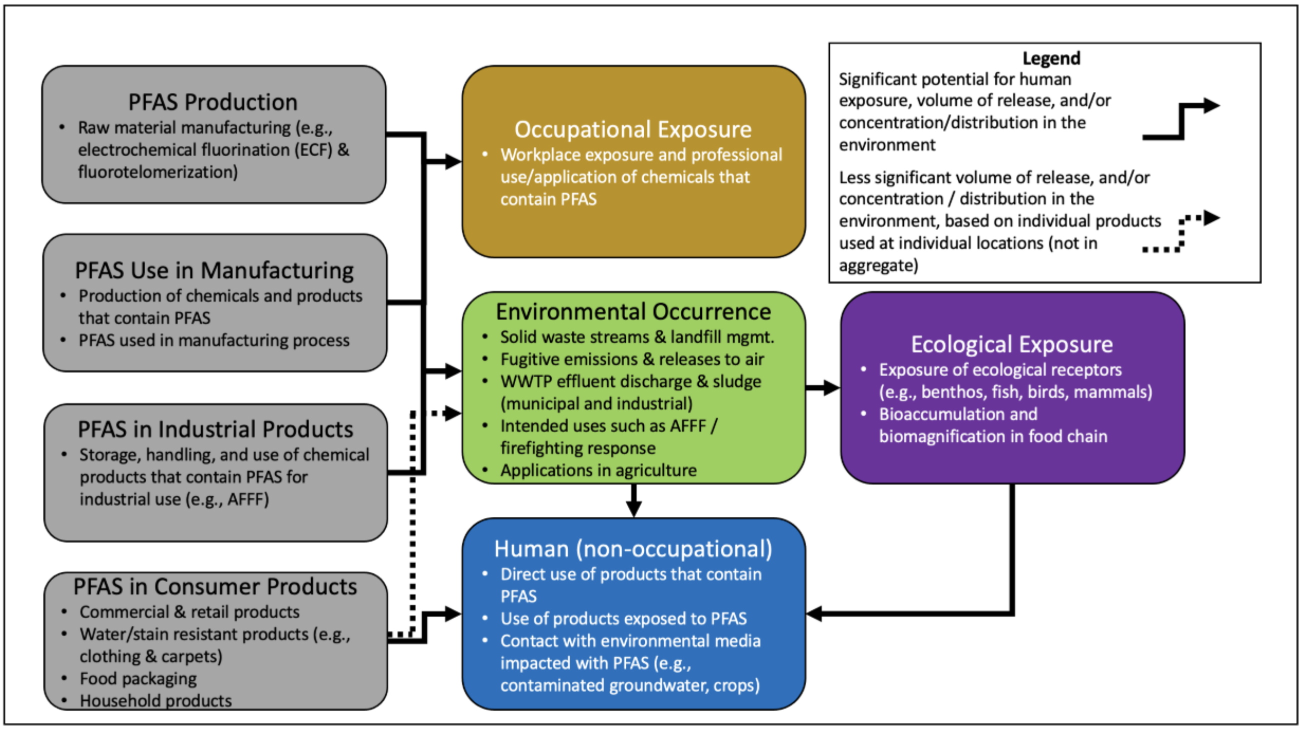


Figure 2-2. Generalized PFAS uses and relative exposure and environmental impact potential from PFAS life cycle.

This figure is not exhaustive with regard to all sources or release mechanisms from those sources. Multiple sources may exist at a site, and the relative potential of exposure and environmental impact may vary based on several considerations. Due to the widespread use of PFAS in commercial and consumer products, other minor point source or diffuse releases of PFAS to the environment may occur during use and disposal of some PFAS-containing products. Although these may result in locally significant environmental impacts, these releases typically affect smaller geographic areas and have lower total PFAS mass than major sources, such as PFAS chemical manufacturing, PFAS use in certain industries, and some applications of certain firefighting foams.

Different PFAS products and sources differ in their relative environmental significance, volumes released, distribution mechanisms, area affected, and relative concentration of impacted media. For instance, nonpolymer PFAS used in Class B firefighting foam may impact a moderate area near the source and may exhibit high concentrations in impacted media. In contrast, a similar volume of nonpolymer PFAS air emissions from a fluoropolymer manufacturing facility may be more widely dispersed and present at lower concentrations in impacted media.

The type of PFAS involved also determines the relative environmental significance. Nonpolymer PFAS (both per- and polyfluorinated) and some side-chain fluorinated polymer PFAS are likely to pose greater risks when released to the environment than certain fluoropolymer sources, such as the fluoropolymers PTFE, fluorinated ethylene-propylene (FEP), perfluoroalkoxy polymer (PFA), and ethylene tetrafluoroethylene (ETFE). These fluoropolymers are considered to be polymers of low concern (Section 2.2.2.1) because they are relatively stable, insoluble in the environment, and not bioavailable (Henry et al. 2018). However, environmental impact from the production or manufacturing uses of fluoropolymers can pose a significant risk if emissions are not properly controlled at the industrial site. Also, releases to the environment from the disposal of fluoropolymers cannot be ruled out, as nonpolymer PFAS (such as the PFAAs used as polymerization aids) may be found at trace levels as impurities and byproducts in some fluoropolymer products (3M Company 1999). Many fluoropolymers may be resistant to transformation. For example, in one study, PTFE did not significantly transform under certain incineration conditions (Aleksandrov et al. 2019). However, research suggests side-chain fluorinated polymers are likely to break down to nonpolymer PFAS over time (Li et al. 2018). For example, commercial fluorotelomer-based polymers (a kind of side-chain fluorinated polymer) have been documented to biotransform under environmental conditions (Washington et al. 2015) and to abiotically transform by hydrolysis under environmental and consumer-use conditions (Washington and Jenkins 2015). For additional information on transformation of polyfluorinated PFAS, see Section 5.4; transformation of PFAS polymers is discussed in Section 5.4.5.

Finally, another consideration regarding environmental impacts is the issue of anthropogenic (human-caused, not naturally occurring) ambient or anthropogenic “background” levels of PFAS. As discussed in Section 6, the long duration of PFAS use and their release from many types of sources may have resulted in low-level contamination of environmental media worldwide. Cousins et al (2022) compares concentrations in environmental media to proposed guidelines from USEPA, Denmark, the Netherlands, and the European Union. The implications of ambient levels of PFAS should be considered in evaluating exposures and risk levels, establishing site action levels and cleanup goals, and identifying PFAS sources.

Updated September 2023.

2.2 Chemistry, Terminology, and Acronyms

This section focuses on chemistry, terminology, names, and acronyms for those PFAS most commonly reported in the environment, identified in scientific literature, and those PFAS most commonly tested for by current analytical methods. Other important classes of PFAS are introduced. This section also introduces the chemical manufacturing processes that influence the types of PFAS that are found in the environment.

The definition of PFAS continues to evolve to reflect continued study of these compounds and takes different forms depending on the regulatory body, operational criteria used, and the intended scope and application of the included list of chemicals. There is no universally accepted definition of PFAS. However, in general, PFAS are compounds characterized as having carbon atoms linked to each other and bonded to fluorine atoms at most or all of the available carbon bonding sites.

Table 2-1 provides examples of several definitions of PFAS (Hammel et al. 2022) developed by several authoritative agencies and researchers.

Table 2-1. Examples of PFAS definitions *(Hammel et al. 2022, Table 2)(CC BY-NC-ND 4.0)*

Source of Definition	Year Defined	Definition	Additional Comments
Buck et al.	2011	"highly fluorinated aliphatic substances that contain one or more carbon (C) atoms on which all the hydrogen (H) substituents (present in the nonfluorinated analogues from which they are notionally derived) have been replaced by fluorine (F) atoms, in such a manner that they contain the perfluoroalkyl moiety C_nF_{2n+1} –."	Buck et al. (2011) is an open-access paper that provides a detailed explanation of PFAS terminology, classification, and origins, and recommends specific and descriptive terminology, names, and acronyms for PFAS.
OECD	2021	"PFASs, including perfluorocarbons, that contain a perfluoroalkyl moiety with three or more carbons (i.e. –C_nF2n–, n ≥ 3) or aperfluoroalkylether moiety with two or more carbons (i.e.–$C_nF2_nOC_mF_{2m}$ -, n and m ≥ 1)."	Updated in 2021
OECD	2021	"fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e. with a few noted exceptions, any chemical with at least a perfluorinated methyl group (–CF3) or a perfluorinated methylene group (–CF2–) is a PFAS."	OECD (2021) expanded the Buck et al.(2011) definition to include chemicals that contain the – C_nF_{2n} – moiety in addition to the C_nF_{2n+1} – moiety, which encompasses chemicals with both ends of the carbon-fluorine chain connected to a hydrogen or a functional group, as well as cyclic analogs of linear PFAS.

Source of Definition	**Year Defined**	**Definition**	**Additional Comments**
Gluge et al.	2020	In addition to substances containing C_nF_{2n+1}, where n ≥ 1, it also "includes (i) substances where a perfluorocarbon chain is connected with functional groups on both ends, (ii) aromatic substances that have perfluoroalkyl moieties on the side chains, and (iii) fluorinated cycloaliphatic substances. Additionally, "polymeric PFAS with the $–CF_2–$ moiety and non-polymeric PFASwith the $–CF_2–CF_2–$ moiety [excluding] non-polymericsubstances that only contain a $–CF_3$ or $–CF_2–$ moiety, with the exception of perfluoroalkylethers and per- andpolyfluoroalkylether-based substances. For these two PFAS groups, substances with a $–CF_2OCF_2–$ or $–CF_2OCFHCF–$ moietyare also included."	Glüge et al. (2020) acknowledged the Buck et al. (2011) and OECD (2018) definitions while also considering the definition of PFAS to include: • substances in which a perfluorocarbon chain is connected with functional groups on both ends • aromatic substances that have perfluoroalkyl moieties on the side chains • fluorinated cycloaliphatic substances.
TURA Program, Massachusetts (TURA 2023)	2023	"Certain PFAS not otherwise listed includes those PFAS thatcontain a perfluoroalkyl moiety with three or more carbons (e.g., $–C_nF_{2n}–$, n ≥ 3; or $CF_3–C_nF_{2n}–$, n ≥ 2) or a perfluoroalkylethermoiety with two or more carbons (e.g., $–C_nF_{2n}OC_mF_{2m}$_ or $–C_nF_{2n}OC_mF_m$, n and m ≥ 1), wherein for the example structures shown the dash (_) is not a bond to a hydrogen and may represent a straight or branched structure, that are not otherwise listed."	
USEPA OPPT	2021	".a structure that contains the unit $R-CF_2-CF(R')(R")$, where R, R', and R" do not equal "H" and the carbon-carbon bond is saturated (note: branching, heteroatoms, and cyclic structures are included)."	Chemicals for review under TSCA to evaluate human health and environmental risks
NDAA, WA, CA, VT, ME	2019, 2020, 2021	Organic chemicals containing at least 1 fully fluorinated carbon atom	Authorities whose legislation defines PFAS as a class of fluorinated organic chemicals containing at least one fully fluorinatedcarbon atom.
USEPA CCL5		"For the purposes of CCL 5, the structural definition of per- and polyfluoroalkyl substances (PFAS) includes chemicals that contain at least one of these three structures:$R-(CF_2)-CF(R')R''$, where both the CF_2 and CF moieties are saturated carbons, and none of the R groups can be hydrogen$R-CF_2OCF_2-R'$, where both the $_{CF2}$ moieties are saturated carbons, and none of the R groups can be hydrogen$CF_3C(CF_3)RR'$, where all the carbons are saturated, and none of the R groups can be hydrogen."	The USEPA CCL5 definition is less inclusive that the OECD definition, but it is more inclusive than the USEPA TSCA definition.

The USEPA's CompTox Chemicals Dashboard (https://comptox.epa.gov/dashboard/chemical-lists/PFASMASTER) provides a large publicly available resource for PFAS structures and predicted properties (Williams et al. 2017; Williams et al. 2022). This effort has taken two approaches to defining PFAS. The first, denoted PFASMASTER (USEPA 2020), was based on a simple join, or combination, of publicly available lists of PFAS chemicals reported by other entities, such as the OECD (2018) report. The second approach applied a small set of structure filters to the entire EPA DSSTox database (currently exceeding 1,200,000 substances), resulting in a list containing more than 8,000 PFAS structures, denoted PFASSTRUCTV3 (USEPA 2020); the most current version is PFASSTRUCTV5 (USEPA 2022) containing more than 14,000 structures. Please check USEPA's CompTox Chemicals Dashboard for the most current version. The PFASMASTER file currently exceeds 12,000 substances and includes both PFAS structures (from PFASSTRUCV5) and structures and non-structurable chemicals (such as mixtures and polymers) from combining several public PFAS lists. Hence, the structure-based filters used in this effort expand the PFAS definition beyond the Buck et al. (2011) and OECD (2021) definitions and are designed to fully encompass publicly available PFAS lists, as well as to be inclusive of small, fluorinated chemicals of potential concern to USEPA. The most current PFASSTRUCTV5 uses a combination of four substructural filters (see Figure 2-3) and/or a threshold of 30% fluorine without hydrogen based on molecular formula count (not weight). The substructural filters (shown in Figure 2-3) are designed to be simple, reproducible and transparent, yet general enough to encompass the largest set of structures having sufficient levels of fluorination to potentially be considered PFAS. (USEPA 2022).

Definitions of PFAS: Buck et al. (2011)definition: "highly fluorinated aliphatic substances that contain one or more carbon (C) atoms on which all the hydrogen (H) substituents (present in the nonfluorinated analogues from which they are notionally derived) have been replaced by fluorine (F) atoms, in such a manner that they contain the perfluoroalkyl moiety CnF2n+1 –." OECD (2021) definition: "fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e. with a few noted exceptions, any chemical with at least a perfluorinated methyl group (–CF3) or a perfluorinated methylene group (–CF2–) is a PFAS."

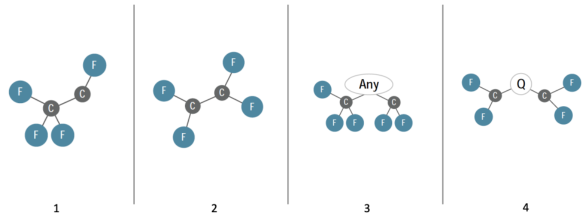


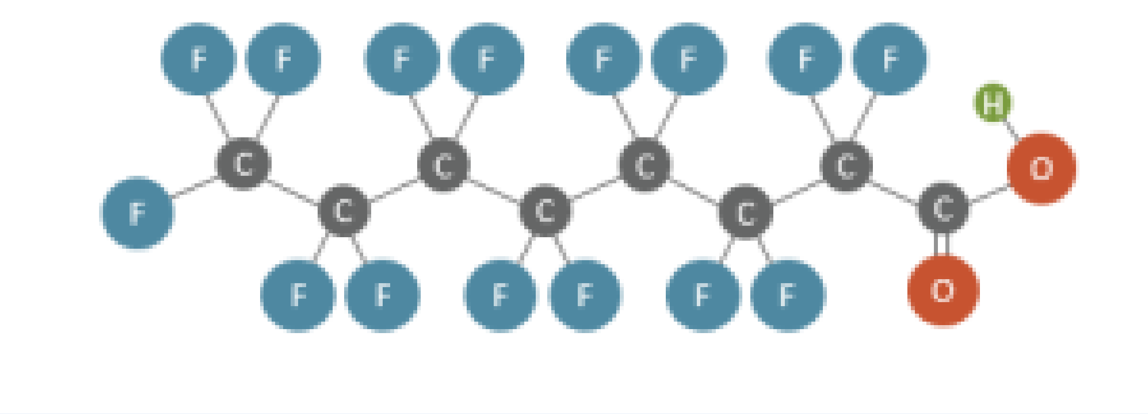
Figure 2-3. Four Substructural Filters of PFAS Used in Development of USEPA's CompTox Dashboard for PFAS (USEPA 2022)

Note: Q can be any of the following atoms: B, O, N, P, S or Si. *Source: Molecule figures M. Olson, Trihydro. Used with permission.*

Whereas some PFAS definitions such as provided by USEPA's CompTox Dashboard are designed to be broadly inclusive, definitions used in regulatory applications often must be more circumscribed and precisely worded. Examples of definitions used in regulatory applications include those used by USEPA TSCA and the USEPA Drinking Water Contaminant Candidate List 5 (CCL5); see Table 2.1. Other states may have their own definition of PFAS (see the Regulatory Programs Summary Table). For example, the state of Maine defines PFAS as substances that include any member of the class of fluorinated organic chemicals containing at least one fully fluorinated carbon atom (Maine State Legislature 2021).

General Concepts of Organofluorine Chemistry for PFAS

Organofluorine Chemistry:A branch of organic chemistry involving organic molecules with a carbon-fluorine bond. Organofluorine molecules have many commercial uses. They include PFAS, such as PFOA, shown below:



Example PFOA molecule, acid form

Source: M. Olson, Trihydro. Used with permission.

Gray spheres represent carbon atoms linked together in a chain; there are eight of them, so “octane” is used in the name. Blue spheres represent fluorine atoms bonded to carbon atoms. Red spheres represent oxygen atoms. Green sphere represents a hydrogen atom that dissolves away in water, which makes this an acid. Fluorine atoms are attached to all possible bonding sites, making this perfluorinated. If some of the fluorine atoms were replaced by other atoms (such as oxygen or hydrogen), it would be polyfluorinated. Without the hydrogen, the “head end” takes on a negative charge and can bond to things through electrostatic attraction. The fluorine “tail end” is strong and stable, giving it lipid- and water-repelling properties, but also making it persistent in the environment.

Isomer: A molecule with the same molecular formula as another molecule, but with a different chemical structure. Isomers contain the same number of atoms of each element, but have different arrangements of their atoms. See Figure 2-15 for an example; linear and branched PFOS contain the same number of carbon, fluorine, oxygen, and sulfur atoms, but these atoms are arranged differently depending on whether it is a linear or branched isomer of PFOS.

Homologue Groups and Homologous Series: A group of organic compounds, usually listed in order of increasing size, that has a similar structure (and therefore also similar properties) and whose structures differ only by the number of carbon atoms in the chain. For example, all of the linear and branched isomers of PFOS would be in the C8 homologue group, while all of the linear and branched isomers of perfluorohexane sulfonic acid (PFHxS) would be in the C6 homologue group. The C_4-C_{12} PFSAs are a homologous series of perfluoroalkane sulfonates.

Throughout Section 2, the Buck et al. (2011) definition has been used for simplicity of discussion in the depiction of naming conventions of PFAS.

2.2.1 Naming Convention Considerations

There is confusion among the environmental community and the public due to overgeneralization when describing PFAS and the lack of consistent naming of specific PFAS. The use of consistent naming conventions would reduce confusion and support clearer communication (Buck et al. 2011; Wang et al. 2017).

“PFAS,” not “PFASs”: The acronym “PFAS” stands for “per- and polyfluoroalkyl substances.” No single chemical within the PFAS family can be both perfluorinated and polyfluorinated, so by definition “PFAS” is plural and a small “s” is not needed. Some authors elect to add a small “s” to this acronym (PFASs) to emphasize the fact that it is plural, but it is not needed. When referring to a single chemical within the PFAS family, it is more accurate to simply name that specific chemical.

Consistent naming also helps to distinguish PFAS from other organic compounds that contain fluorine. As defined in the literature, PFAS may include only one fluorinated aliphatic (carbon chain) substance. Alkyl/aliphatic groups are fully saturated carbon chains, which can be either cyclic, non-cyclic, branched or unbranched. Alkyl and aliphatic can be used interchangeably. Depending on the definition, PFAS may or may not include fluorinated compounds that contain aromatic (carbon ring) features in their structures (for example, active pharmaceutical ingredients, crop protection agents, or chlorofluorocarbons [refrigerants]) (Gaines, Sinclair, and Williams 2023; Glüge et al. 2020; Hammel et al. 2022). The inclusion of aromatic components in a chemical structure in the PFAS classification varies depending on what definition is applied. As Gaines, Sinclair, and Williams 2023 describes, including aromatics in a PFAS definition confounds things as the "PFAS" acronym includes the word "alkyl" that does not include aromatics. The authors go on to say that the "A" in PFAS could also be used to mean both aliphatic and aromatic, but this could also cause confusion as PFAS have not been used widely with this interpretation.

The use of nonspecific acronyms, such as perfluorinated compound (PFC), has hampered clarity of investigative results. The acronym "PFC" is poorly defined in the scientific literature, but typically refers to "perfluorinated compounds." "PFC" is widely used in the climate community, referring to perfluorocarbons, which are a subset of PFAS. PFC does not include "polyfluorinated substances," which are increasingly recognized as important contaminants at many PFAS sites.

CAS numbers are another helpful tool for clearly identifying the chemical that is being referenced; however, care must be taken in selecting the correct CAS number to avoid confusion regarding the chemistry and behavior of the chemical being described. Some PFAS may exist in various ionic states, such as acids, anions (negatively charged), cations (positively charged), and zwitterions (both positively and negatively charged dipolar molecules), and each has its own CAS number (and some have no CAS number). The ionic state determines electrical charge and physical and chemical properties, which in turn control fate and transport in the environment (Section 5) and potential human health and ecological effects (Section 7). The ionic state of individual PFAS can result in significantly different physical and chemical properties (Section 4), such as solubility, volatility, and bioaccumulative potential.

Some chemicals in the PFAS family can exist in various ionic states (for example, acids, anions, cations), which have important implications for their chemical and physical properties. In most cases for PFAAs, this section uses the anionic form of a given PFAS name, as this is the state in which most PFAAs exist in the environment.

International Union of Pure and Applied Chemistry (IUPAC) (https://iupac.org) nomenclature may also be used for identifying PFAS chemicals. The IUPAC nomenclature system is typically used in more formal literature such as patents. Examples of the IUPAC naming convention are provided below.

- PFOA: 2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-Pentadecafluorooctanoic acid
- PFOS: 1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluorooctane-1-sulfonic acid

In the future, it may be necessary to expand the current naming conventions and acronym approaches to ensure that standardized naming is available for additional members of the PFAS family of compounds.

2.2.2 Introduction to the PFAS Family

PFAS are comprised of a wide variety of molecules with different physical and chemical properties and molecular weights with perfluoroalkyl moieties as common structural features, as note by Cousins et al. (2020), who identified specifically:

> *"…the PFAS class comprises distinct substances with very different structures and properties: high-molecular-weight polymers and high-molecular-weight non-polymers; neutral, anionic, cationic and zwitterionic substances; solids, liquids, and gases; highly reactive and non-reactive (inert) substances; soluble and insoluble substances; and volatile and involatile substances. In the environment, some PFAS are mobile and others immobile, and some bioaccumulate while others do not."*

This variety of PFAS with diverse properties is organized in the form of a PFAS family tree (Figure 2-4) that includes two primary classes: polymers and nonpolymers. Each class may contain many subclasses, groups, and subgroups, some of which are shown in the figure. This document focuses primarily on those nonpolymer PFAS most commonly detected in the environment and those PFAS that may be significant as "precursors" that can transform to more persistent forms.

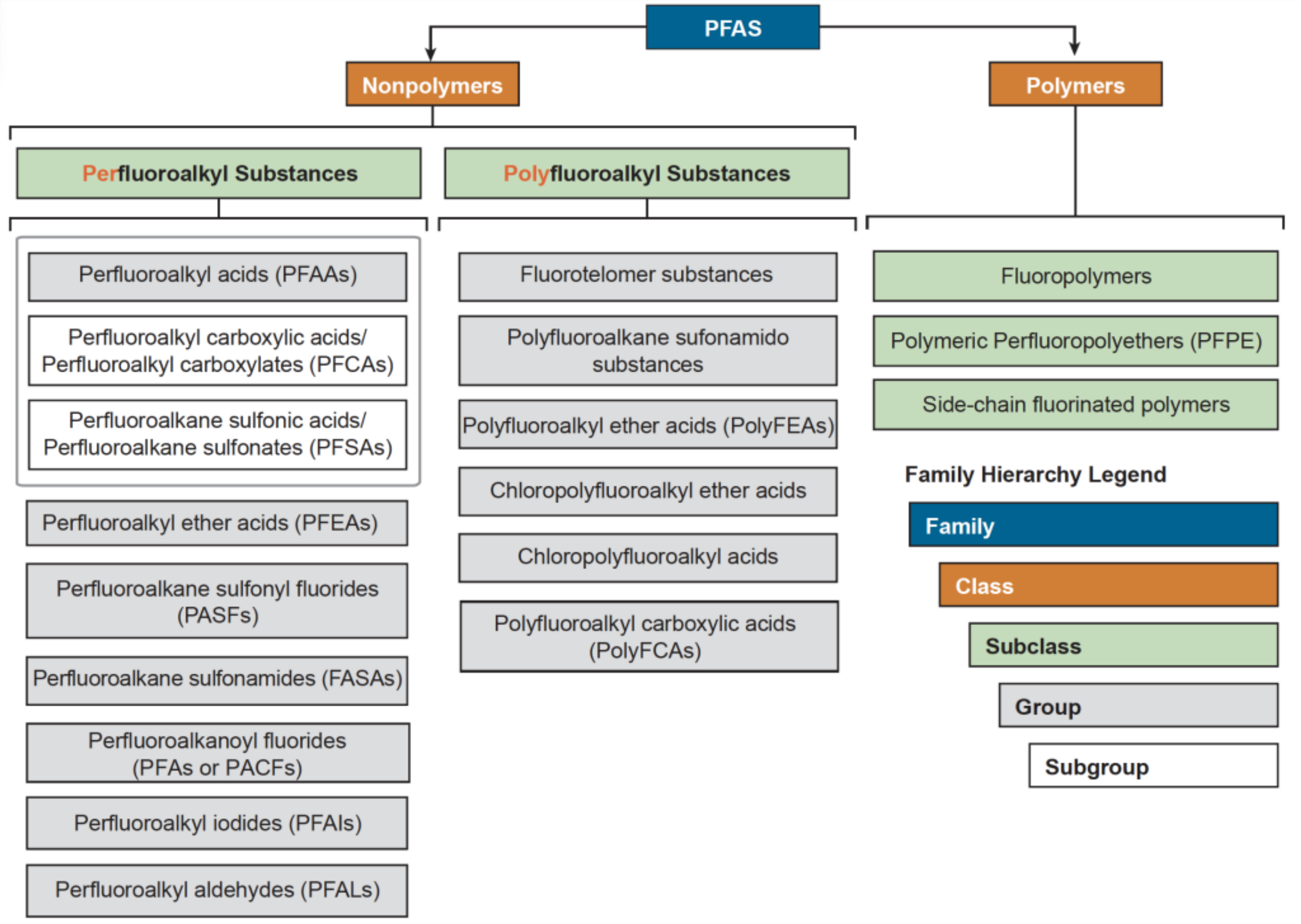
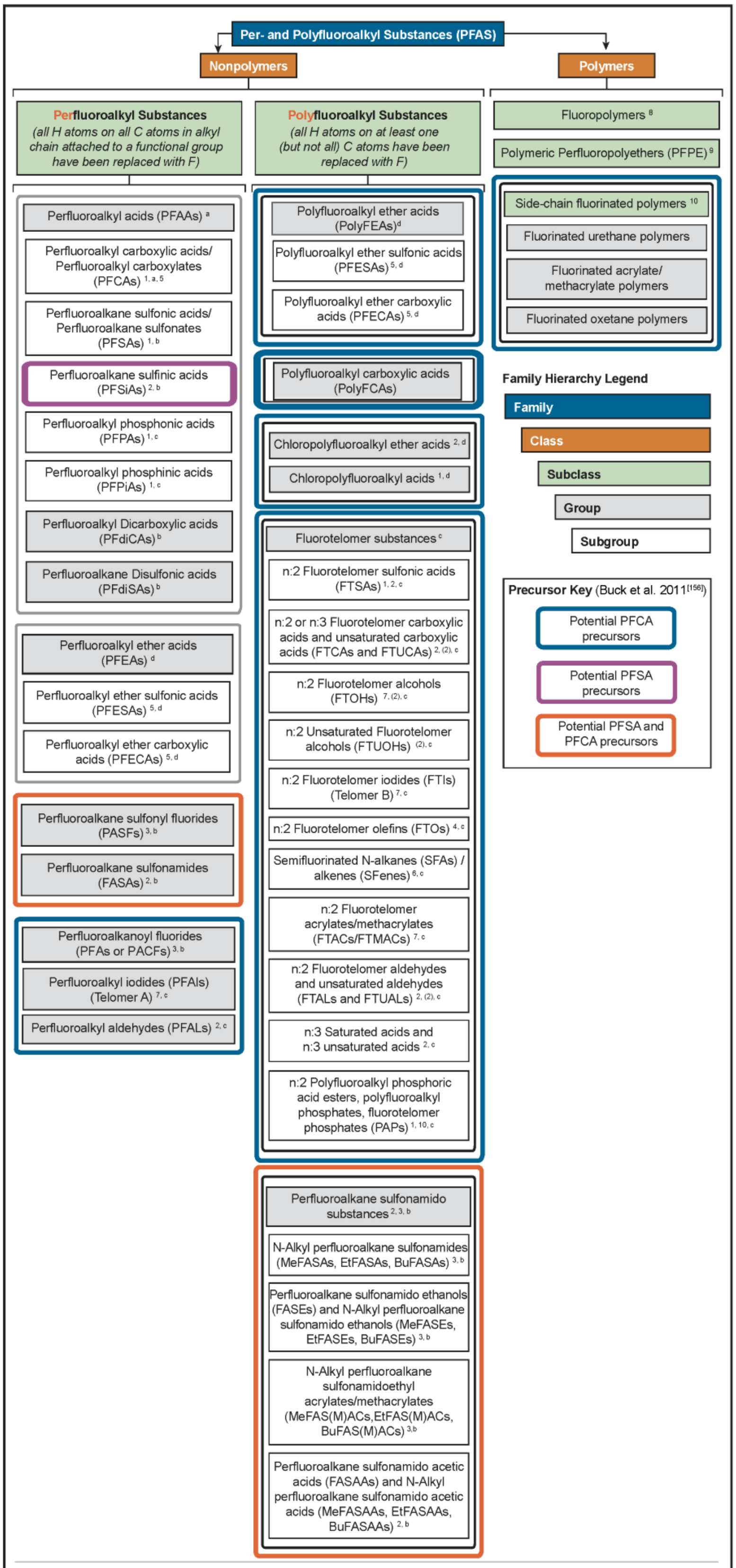


Figure 2-4. The PFAS family.

The family tree is further expanded in Figure 2-5, based on nomenclature provided in Buck et al. (2011), Organization for Economic Co-operation and Development OECD (2015), and Wang et al. (2017), with further introduction to some of these chemicals provided later in this section. Future updates to the family tree and nomenclature are expected to be necessary given the evolving public knowledge of these compounds. For example, other PFAS without analytical standards are being identified using nontarget analyses by research laboratories (Section 11). These PFAS do not necessarily have associated CAS numbers but are being identified by molecular structure. Naming conventions and categories of PFAS are developed as a means to communicate, manage, and address this class of many chemicals, which can include alternate naming conventions and a variety of rationales for assigning categories.



Manufacturing Process Legend

(a) Manufactured by either ECF or fluorotelomerization
(b) Manufactured by ECF
(c) Manufactured by fluorotelomerization
(d) Other process

Notes

The acronym PFECA is utilized for both per and polyfluoroalkyl ether carboxylic acids and the acronym PFESA is utilized for both per and polyfluoroalkyl ether sulfonic acids. When using these acronyms, it is important to be clear as to the specific group of chemicals being referenced (i.e., per or poly).

FASAs biodegrade to PFSAs, with the potential to degrade to PFSAs and PFCAs in the atmosphere – see Figure 2-10.

The family tree is based on the PFAS definition provided in Buck et al. 2011[156] and OECD 2021[2318]

PFAS Use Legend

(1) Surfactants
(2) Intermediate transformation product
(3) Major raw material for ECF-based surfactants and surface protection products
(4) Raw material for surfactants and surface protection products
(5) Includes some fluoropolymer polymerization aids
(6) Ski wax, medical applications
(7) Major raw material for fluorotelomer-based surfactants and surface protection products
(8) High molecular weight polymeric plastics such as PTFE
(9) A broad class of polymers used largely as lubricants
(10) Used for surface protection

Figure 2-5. PFAS family tree. *Adapted from a graphic provided courtesy of Paul Caprio, EA Engineering.* A stand-alone PDF version of Figure 2-5 is available.

2.2.2.1 Polymer PFAS

Polymers are large molecules formed by combining many identical smaller molecules (or monomers, which are shorter chain molecules with no repeating units) in a repeating pattern.

The PFAS polymer class includes fluoropolymers, polymeric perfluoropolyethers, and side-chain fluorinated polymers (Henry et al. 2018; Buck et al. 2011; Wang et al. 2013):

- Fluoropolymers contain a carbon-only polymer backbone with fluorines directly attached to the carbon. Fluoropolymers include polymers like PTFE, ETFE, copolymer FEP, and PFA, which were historically made using processing aids ammonium perfluorooctanoate (APFO) or sodium perfluorooctanoate (NaPFO), which are salts of perfluorooctanoic acid (PFOA). Fluoropolymers also include polyvinylidene fluoride (PVDF), which was historically made using ammonium perfluorononanoate (APFN), the ammonium salt of perfluorononanoic acid (PFNA) (OECD 2015; Buck et al. 2011).
- The specific fluoropolymers PTFE, FEP, ETFE, and PFA have been referred to as “polymers of low concern” in two studies. Henry et al. (2018) notes that these specific fluoropolymers have high molecular weight and are extremely stable and PTFE has been demonstrated not to be bioavailable (Henry et al. 2018). Polymers of low concern are reported to pose little environmental or health risk once in a consumer product, and based on this, Henry et al. (2018) suggested that “polymers of low concern” should be considered separately from other PFAS when evaluating risk. An additional study (Korzeniowski et al. (2023)) describes the composition, uses, performance properties and functionalities of 14 fluoropolymers, including fluoroplastics and fluoroelastomers, and presents data to show that they satisfy the widely accepted polymer hazard assessment criteria to be considered polymers of low concern (PLC). Further, the study results show that fluoropolymers are a distinct and different group of PFAS and should not be grouped with other PFAS for hazard assessment or regulatory purposes.
- However, during the manufacture of some fluoropolymers, nonpolymer PFAS are used as processing aids and may be found as impurities in some fluoropolymer products (3M Company 1999; CalEPA 2018; see Section 5.4.5). For this reason, in order to prevent potential releases of nonpolymer PFAS processing aids (see AFPO and NaPFO discussion above) and short-chain polymeric byproducts/impurities, such as unreacted monomers, environmental controls are necessary during the manufacturing and further processing of fluoropolymers. However, it should be noted that another study (Lohmann et al. 2020) found that there was insufficient evidence to consider fluoropolymers as being of low concern for environmental and human health and that group of fluoropolymers should not be given a blanket exemption from regulatory review. According to Lohmann et al. (2020), the assessment and management of fluoropolymer products should consider the complete life cycle, including associated emissions during production and disposal.
- Polymeric perfluoropolyethers (PFPE) contain a carbon and oxygen polymer backbone with fluorines directly attached to carbon. Relatively little is known about these chemicals in the environment.
- Side-chain fluorinated polymers contain a nonfluorinated polymer backbone, off of which fluorinated side chains branch. These PFAS include fluorinated urethane polymers, fluorinated acrylate/methacrylate polymers, and fluorinated oxetane polymers. A few side-chain fluorinated polymers can become precursors for PFAAs, (Section 2.2.3.1) by transformation, when the point of connection of a fluorinated side chain on a polymer is broken to release a PFAA, or by release of fluorinated monomer residuals, or both.

2.2.2.2 Nonpolymer PFAS

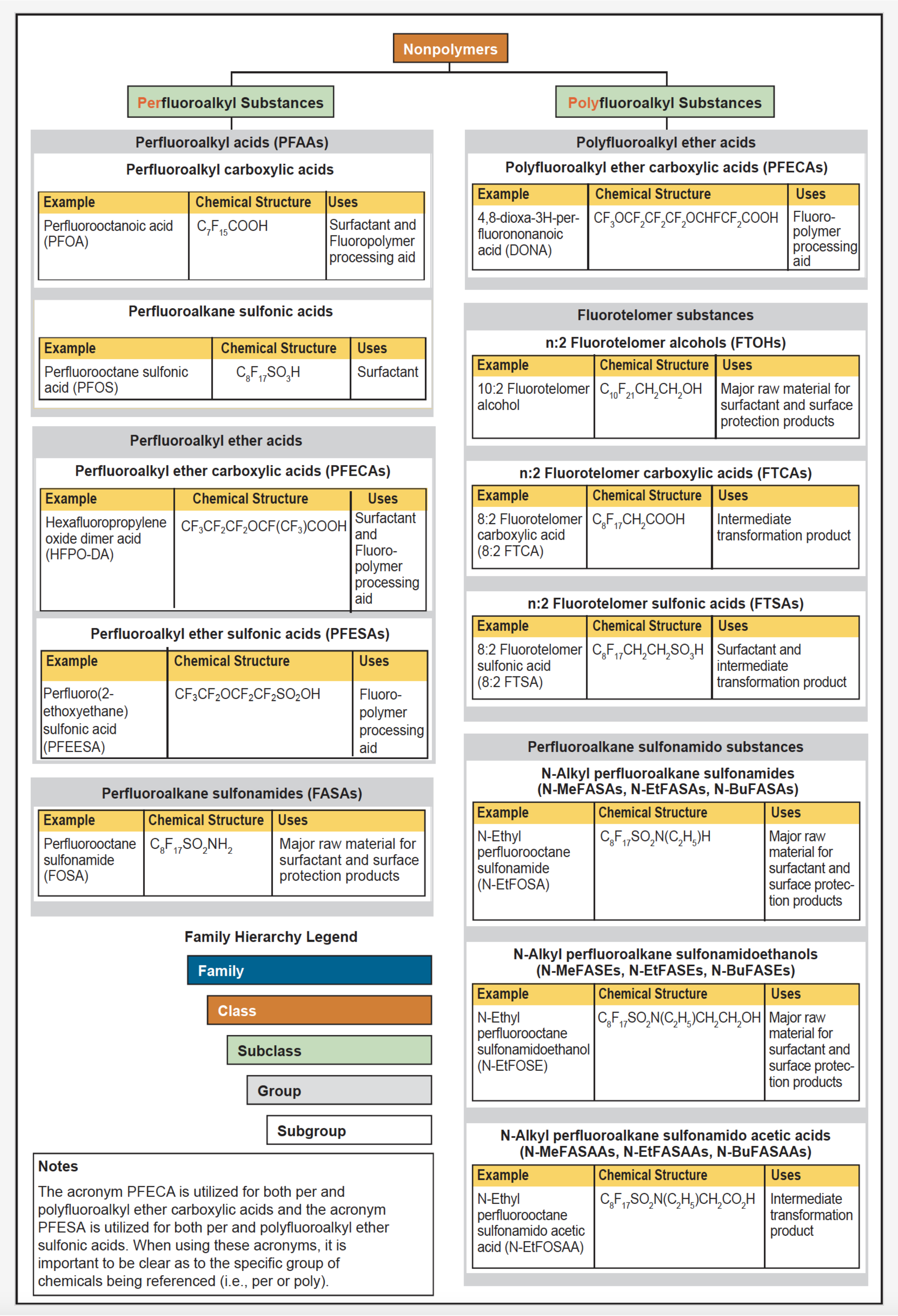
Nonpolymer PFAS encompass two major subclasses: perfluoroalkyl substances and polyfluoroalkyl substances, which include many groups and subgroups of chemicals. Figure 2-6 provides general classification and chemical structures, examples of each group and/or subgroup, and examples of the primary uses of the nonpolymer PFAS highlighted in Figure 2-4 and Figure 2-5.

Nonpolymer PFAS were selected as the focus of this document because:

- they are included in most laboratory PFAS analyte lists (Section 11)
- they are the PFAS most commonly detected (to date) in humans, biota, and other environmental media and

appear to be relatively more abundant at PFAS investigation sites (Section 6)

- data may be available regarding potential human health and ecological effects from environmental exposure for some of these chemicals (Section 7)
- state or federal standards or guidance values may exist or be under development for some of these chemicals (Section 8).



Nonpolymers

Perfluoroalkyl Substances

Perfluoroalkyl acids (PFAAs)

Perfluoroalkyl carboxylic acids

Example	Chemical Structure	Uses
Perfluorooctanoic acid (PFOA)	$C_7F_{15}COOH$	Surfactant and Fluoropolymer processing aid

Perfluoroalkane sulfonic acids

Example	Chemical Structure	Uses
Perfluorooctane sulfonic acid (PFOS)	$C_8F_{17}SO_3H$	Surfactant

Perfluoroalkyl ether acids

Perfluoroalkyl ether carboxylic acids (PFECAs)

Example	Chemical Structure	Uses
Hexafluoropropylene oxide dimer acid (HFPO-DA)	$CF_3CF_2CF_2OCF(CF_3)COOH$	Surfactant and Fluoropolymer processing aid

Perfluoroalkyl ether sulfonic acids (PFESAs)

Example	Chemical Structure	Uses
Perfluoro(2-ethoxyethane) sulfonic acid (PFEESA)	$CF_3CF_2OCF_2CF_2SO_2OH$	Fluoropolymer processing aid

Perfluoroalkane sulfonamides (FASAs)

Example	Chemical Structure	Uses
Perfluorooctane sulfonamide (FOSA)	$C_8F_{17}SO_2NH_2$	Major raw material for surfactant and surface protection products

Polyfluoroalkyl Substances

Polyfluoroalkyl ether acids

Polyfluoroalkyl ether carboxylic acids (PFECAs)

Example	Chemical Structure	Uses
4,8-dioxa-3H-perfluorononanoic acid (DONA)	$CF_3OCF_2CF_2CF_2OCHFCF_2COOH$	Fluoropolymer processing aid

Fluorotelomer substances

n:2 Fluorotelomer alcohols (FTOHs)

Example	Chemical Structure	Uses
10:2 Fluorotelomer alcohol	$C_{10}F_{21}CH_2CH_2OH$	Major raw material for surfactant and surface protection products

n:2 Fluorotelomer carboxylic acids (FTCAs)

Example	Chemical Structure	Uses
8:2 Fluorotelomer carboxylic acid (8:2 FTCA)	$C_8F_{17}CH_2COOH$	Intermediate transformation product

n:2 Fluorotelomer sulfonic acids (FTSAs)

Example	Chemical Structure	Uses
8:2 Fluorotelomer sulfonic acid (8:2 FTSA)	$C_8F_{17}CH_2CH_2SO_3H$	Surfactant and intermediate transformation product

Perfluoroalkane sulfonamido substances

N-Alkyl perfluoroalkane sulfonamides (N-MeFASAs, N-EtFASAs, N-BuFASAs)

Example	Chemical Structure	Uses
N-Ethyl perfluorooctane sulfonamide (N-EtFOSA)	$C_8F_{17}SO_2N(C_2H_5)H$	Major raw material for surfactant and surface protection products

N-Alkyl perfluoroalkane sulfonamidoethanols (N-MeFASEs, N-EtFASEs, N-BuFASEs)

Example	Chemical Structure	Uses
N-Ethyl perfluorooctane sulfonamidoethanol (N-EtFOSE)	$C_8F_{17}SO_2N(C_2H_5)CH_2CH_2OH$	Major raw material for surfactant and surface protection products

N-Alkyl perfluoroalkane sulfonamido acetic acids (N-MeFASAAs, N-EtFASAAs, N-BuFASAAs)

Example	Chemical Structure	Uses
N-Ethyl perfluorooctane sulfonamido acetic acid (N-EtFOSAA)	$C_8F_{17}SO_2N(C_2H_5)CH_2CO_2H$	Intermediate transformation product

Family Hierarchy Legend

- Family
- Class
- Subclass
- Group
- Subgroup

Notes

The acronym PFECA is utilized for both per and polyfluoroalkyl ether carboxylic acids and the acronym PFESA is utilized for both per and polyfluoroalkyl ether sulfonic acids. When using these acronyms, it is important to be clear as to the specific group of chemicals being referenced (i.e., per or poly).

Figure 2-6. Examples of some nonpolymer PFAS subclasses discussed in this document.

Source: Adapted with permission from Buck, R.C., J. Franklin, U. Berger, J. M. Conder, I. T. Cousins, P. de Voogt, A. A. Jensen, K. Kannan, S. A. Mabury, and S. P. van Leeuwenet. 2011. "Perfluoroalkyl and Polyfluoroalkyl Substances in the Environment: Terminology, Classification, and Origins." Integrated Environmental Assessment and Management, 7:513-541. Open access. Copyright 2011 SETAC. http://dx.doi.org/10.1002/ieam.258

2.2.3 Perfluoroalkyl Substances

Perfluoroalkyl substances are fully fluorinated alkane molecules that include (but are not limited to):

- perfluoroalkyl acids (PFAAs) and
- perfluoroalkane sulfonamides (FASAs).

The basic chemical structure is a chain (or *tail*) of two or more carbon atoms with a charged functional group (or *head*) attached at one end. The functional groups commonly are carboxylates or sulfonates, but other forms are also detected in the environment. Fluorine atoms are attached to all possible bonding sites along the carbon chain of the tail, except for one bonding site on the last carbon where the functional group head is attached. This structure, which is illustrated in Figure 2-7 for PFOS and PFOA, can be written as:

$$\mathbf{C_nF_{2n+1}\text{-}R}$$

where "C_nF_{2n+1}" defines the length of the perfluoroalkyl chain tail, "n" is >2, and "R" represents the attached functional group head. Note that the functional group may contain one or more carbon atoms, which are included in the total number of carbons when naming the compound.

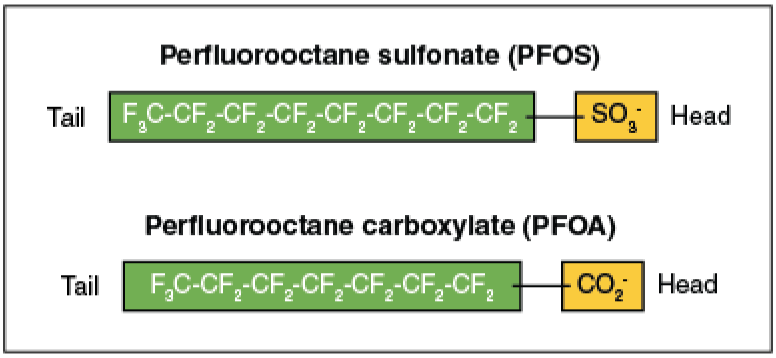


Figure 2-7. The tail and head structure of PFOS and PFOA molecules.

2.2.3.1 Perfluoroalkyl Acids (PFAAs)

PFAAs are some of the least complex PFAS molecules. They are essentially non-degradable under normal environmental conditions. Biotic and abiotic transformation of many polyfluoroalkyl substances may result in the formation of PFAAs. As a result, PFAAs are sometimes referred to as "terminal PFAS" or "terminal transformation products," meaning no further transformation products will form from them under environmental conditions. Polyfluoroalkyl substances that transform to create terminal PFAAs are referred to as "***precursors***." Longer chain PFAAs are not known to biotransform to shorter chain PFAAs.

The PFAA group is divided into two major subgroups (as shown in Table 2-1 and Figure 2-4).

- ***Perfluoroalkyl carboxylic acids*** (PFCAs), or perfluoroalkyl carboxylates, are used commercially and can be formed as terminal transformation products of select precursor polyfluoroalkyl substances, such as fluorotelomer alcohols (FTOHs). An example PFCA is PFOA.
- ***Perfluoroalkane sulfonic acids*** (PFSAs), or perfluoroalkane sulfonates, also are used commercially and can be formed as terminal transformation products of select precursor polyfluoroalkyl substances, such as perfluoroalkane sulfonamido ethanols (FASEs). An example PFSA is PFOS.

Other subgroups of PFAAs are introduced below. Some of those are compounds that are receiving increasing attention, are being added to commercial laboratory target analyte lists, and are being detected in the environment. Other PFAAs include:

- perfluoroalkane sulfinic acids (PFSiAs), associated with the electrochemical fluorination (ECF) process and also occurring as intermediate environmental transformation products
- perfluoroalkyl phosphonic acids (PFPAs) and phosphinic acids (PFPiAs), associated with the fluorotelomerization process and used as surfactants

PFAAs are the group of PFAS that make up the majority of PFAS typically included in commercial laboratory target analyte lists and are the primary PFAS for which federal or state health-based guidance values have been established. As a result, PFAAs tend to drive site investigation and remediation decisions, so it is helpful to understand the naming conventions for this class. Many of the commonly detected PFAAs are denoted using the following structural shorthand acronym:

PFXY where:
PF = perfluoro
X = the carbon chain length (using the same naming conventions as hydrocarbons based on the number of carbons (for example, B for butane or 4 carbons, Pe for pentane or 5 carbons)
Y = the functional group (for example, A = carboxylate or carboxylic acid and S = sulfonate or sulfonic acid)

Table 2-2 illustrates how this naming structure works for the PFCAs and PFSAs, which collectively are referred to as PFAAs.

Table 2-2. Basic naming structure and shorthand for PFAAs

X	Y	Acronym	Name	Formula	CAS No.[1]	DTXSID[2]
B = buta (4 carbon)	A = carboxylate or carboxylic acid	PFBA	Perfluorobutanoate[1]	$C_3F_7CO_2^-$	45048-62-2	80892480
			Perfluorobutanoic acid[1]	C_3F_7COOH	375-22-4	4059916
	S = Sulfonate or sulfonic acid	PFBS	Perfluorobutane sulfonate	$C_4F_9SO_3^-$	45187-15-3	60873015
			Perfluorobutane sulfonic acid	$C_4F_9SO_3H$	375-73-5	5030030
Pe = penta (5 carbon)	A = Carboxylate or carboxylic acid	PFPeA	Perfluoropentanoate	$C_4F_9CO_2^-$	45167-47-3	00892487
			Perfluoropentanoic acid	C_4F_9COOH	2706-90-3	6062599
	S = Sulfonate or sulfonic acid	PFPeS	Perfluoropentane sulfonate	$C_5F_{11}SO_3^-$	175905-36-9	70892479
			Perfluoropentane sulfonic acid	$C_5F_{11}SO_3H$	2706-91-4	8062600
Hx = hexa (6 carbon)	A = Carboxylate or carboxylic acid	PFHxA	Perfluorohexanoate	$C_5F_{11}CO_2^-$	92612-52-7	20892484
			Perfluorohexanoic acid	$C_5F_{11}COOH$	307-24-4	3031862
	S = Sulfonate or sulfonic acid	PFHxS	Perfluorohexane sulfonate	$C_6F_{13}SO_3^-$	108427-53-8	80873012
			Perfluorohexane sulfonic acid	$C_6F_{13}SO_3H$	355-46-4	7040150
Hp = hepta (7 carbon)	A = Carboxylate or carboxylic acid	PFHpA	Perfluoroheptanoate	$C_6F_{13}CO_2^-$	120885-29-2	60892483
			Perfluoroheptanoic acid	$C_6F_{13}COOH$	375-85-9	1037303
	S = Sulfonate or sulfonic acid	PFHpS	Perfluoroheptane sulfonate	$C_7F_{15}SO_3^-$	146689-46-5	8059920
			Perfluoroheptane sulfonic acid	$C_7F_{15}SO_3H$	375-92-8	20892505
O = octa (8 carbon)	A = Carboxylate or carboxylic acid	PFOA	Perfluorooctanoate	$C_7F_{15}CO_2^-$	45285-51-6	40892486
			Perfluorooctanoic acid	$C_7F_{15}COOH$	335-67-1	8031865
	S = Sulfonate or sulfonic acid	PFOS	Perfluorooctane sulfonate	$C_8F_{17}SO_3^-$	45298-90-6	80108992
			Perfluorooctane sulfonic acid	$C_8F_{17}SO_3H$	1763-23-1	3031864

X	Y	Acronym	Name	Formula	CAS No.[1]	DTXSID[2]
N = nona (9 carbon)	A = Carboxylate or carboxylic acid	PFNA	Perfluorononanoate	$C_8F_{17}CO_2^-$	72007-68-2	80892485
			Perfluorononanoic acid	$C_8F_{17}COOH$	375-95-1	8031863
	S = Sulfonate or sulfonic acid	PFNS	Perfluorononane sulfonate	$C_9F_{19}SO_3^-$	474511-07-4	60873010
			Perfluorononane sulfonic acid	$C_9F_{19}SO_3H$	68259-12-1	8071356
D = deca (10 carbon)	A = Carboxylate or carboxylic acid	PFDA	Perfluorodecanoate	$C_9F_{19}CO_2^-$	73829-36-4	40892481
			Perfluorodecanoic acid	$C_9F_{19}COOH$	335-76-2	3031860
	S = Sulfonate or sulfonic acid	PFDS	Perfluorodecane sulfonate	$C_{10}F_{21}SO_3^-$	126105-34-8	00873014
			Perfluorodecane sulfonic acid	$C_{10}F_{21}SO_3H$	335-77-3	3040148
Un = undeca (11 carbon)	A = Carboxylate or carboxylic acid	PFUnA or PFUnDA	Perfluoroundecanoate	$C_{10}F_{21}CO_2^-$	196859-54-8	30892475
			Perfluoroundecanoic acid	$C_{10}F_{21}COOH$	2058-94-8	8047553
	S = Sulfonate or sulfonic acid	PFUnS PFUnDS	Perfluoroundecane sulfonate	$C_{11}F_{23}SO_3^-$	441296-91-9	40904578
			Perfluoroundecane sulfonic acid	$C_{11}F_{23}SO_3H$	749786-16-1	40904573
DoD = dodeca (12 carbon)	A = Carboxylate or carboxylic acid	PFDoDA	Perfluorododecanoate	$C_{11}F_{23}CO_2^-$	171978-95-3	00892482
			Perfluorododecanoic acid	$C_{11}F_{23}COOH$	307-55-1	8031861
	S = Sulfonate or sulfonic acid	PFDoDS	Perfluorododecane sulfonate	$C_{12}F_{25}SO_3^-$	343629-43-6	00904574
			Perfluorododecane sulfonic acid	$C_{12}F_{25}SO_3H$	79780-39-5	20873011
TrD = trideca (13 carbon)	A = Carboxylate or carboxylic acid	PFTrDA	Perfluorotridecanoate	$C_{12}F_{25}CO_2^-$	862374-87-6	20892489
			Perfluorotridecanoic acid	$C_{12}F_{25}COOH$	72629-94-8	90868151
	S = Sulfonate or sulfonic acid	PFTrDS	Perfluorotridecane sulfonate	$C_{13}F_{27}SO_3^-$	NA	00904579
			Perfluorotridecane sulfonic acid	$C_{13}F_{27}SO_3H$	791563-89-8	20904576
TeD = tetradeca (14 carbon)	A = Carboxylate or carboxylic acid	PFTeDA	Perfluorotetradecanoate	$C_{13}F_{27}CO_2^-$	365971-87-5	60892488
			Perfluorotetradecanoic acid	$C_{13}F_{27}COOH$	376-06-7	3059921
	S = Sulfonate or sulfonic acid	PFTeDS	Perfluorotetradecane sulfonate	$C_{14}F_{29}SO_3^-$	343629-46-9	30904582
			Perfluorotetradecane sulfonic acid	$C_{14}F_{29}SO_3H$	1379460-39-5	80904577

NA = not available

[1] Older nomenclature may use butyrate or butyric acid.

[2] Link to DTXSID: https://comptox.epa.gov/dashboard/chemical-lists/PFASMASTER (helpful to use as a means of finding structural depictions and availability of other public data)

Note that for PFCAs, the total number of carbons used for naming the compound includes the carbon in the carboxylic acid functional group (COOH). For example, although PFOA has seven carbons in its fluoroalkyl tail, all eight of the carbons in the molecule are used to name it, hence *perfluorooctanoate*. But in terms of chemical behavior, PFOA would be more analogous to seven-carbon perfluoroheptane sulfonate (PFHpS) than to eight-carbon perfluorooctane sulfonate (PFOS).

Table 2-2 shows the PFAA names and formulas in both the anionic (also referred to as “deprotonated” or negatively charged) and acid (also referred to as protonated or neutral) forms. The anionic form is the state in which PFAAs are found in the environment, except in very rare situations (for example, extremely low pH). The anionic and acid forms of PFAA names are often incorrectly used interchangeably (for example, perfluorooctane sulfonate and perfluorooctane sulfonic acid), and the same acronym (in this case, PFOS) applies to both forms. However, as discussed below and in Section 4, their physical and chemical properties are different, and it is important to know which form is being described.

Until recently, PFCAs and PFSAs have been the subgroups most commonly tested for in the environment; however, a wide range of PFAS with other functional groups exists for which the same “PFXY” shorthand shown above may or may not apply. For naming conventions for these compounds, please refer to Buck et al. (2011).

Long-Chain Versus Short-Chain Distinction
PFAS, predominantly PFAAs, are sometimes described as *long-chain* and *short-chain* as a shorthand way to categorize PFCAs and PFSAs that may behave similarly in the environment; however, it is important not to generalize about PFAA behavior based only on chain length. As recent research suggests, other factors besides chain length may affect bioaccumulation potential of PFAS (Ng and Hungerbühler 2014).

According to the OECD (2013):

- *Long-chain* refers to:
    - PFCAs with eight or more carbons (seven or more carbons are perfluorinated)
    - PFSAs with six or more carbons (six or more carbons are perfluorinated)
- *Short-chain* refers to:
    - PFCAs with seven or fewer carbons (six or fewer carbons are perfluorinated)
    - PFSAs with five or fewer carbons (five or fewer carbons are perfluorinated)

Table 2-3 illustrates the differences in the short-chain and long-chain PFCAs and PFSAs.

Table 2-3. Short-chain and long-chain PFCAs and PFSAs

Number of Carbons	4	5	6	7	8	9	10	11	12
PFCAs	Short-chain PFCAs				Long-chain PFCAs				
	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFUnA	PFDoA
PFSAs	PFBS	PFPeS	PFHxS	PFHpS	PFOS	PFNS	PFDS	PFUnS	PFDoS
	Short-chain PFSAs		Long-chain PFSAs						

Anions Versus Acids
As noted above, the names for the anionic and acid forms of PFAAs are often used interchangeably, but it is critical to know which form is being discussed because of differences in their physical and chemical properties and behavior in the environment (Section 6). Some important things to keep in mind regarding the anionic versus acid forms are:

- Most PFAAs are present in environmental and human matrices in their anionic form. For example, PFOS is present in the environment in the anionic form, perfluorooctane sulfonate.
- Although laboratories may be reporting PFOA or PFOS using the acid form of their name, they are actually measuring the anionic form (for example, perfluorooctanoate or perfluorooctane sulfonate), as this is the form that exists in the environment.
- The acid form and their associated cationic salts have CAS numbers, while the anionic forms may not (Table 2-2). For example, PFOS can exist as different salts (cationic), including sodium, lithium, potassium, or ammonium. Each of these salts will have a different CAS number:
    - PFOS, acid form CAS No.: 1763-23-1
    - PFOS, potassium salt CAS No.: 2795-39-3
    - PFOS, ammonium salt CAS No.: 29081-56-9
- When the salt or acid exists in water or other liquids, it will dissociate (lose its hydrogen or associated ion), and the salt or acid will break off and form the anion (for example, COO– or SO3–). Figure 2-8 illustrates the

dissociation of PFBA.

$$\underset{\text{Perfluorobutanoic acid}}{F_3C\text{-}CF_2\text{-}CF_2\text{-}COOH} \rightleftharpoons \underset{\text{Perfluorobutanoate (+ dissociated proton)}}{F_3C\text{-}CF_2\text{-}CF_2\text{-}CO_2^- + H^+}$$

Figure 2-8. Dissociation of PFBA.

It is most important to distinguish between the acid form and anionic form when reporting the physical and chemical properties. The discussion of PFAS properties in this guidance document generally refers to the anionic form; it will be specifically called out if the acid form is being discussed.

A Note About PFAS Naming in Laboratory Reports (see Section 11)

Even though PFAAs occur as anions in the environment, some laboratories report all of their results in the acidic form, while others may report PFCAs as acids (for example, ***perfluorooctanoic acid****) and PFSAs as anions (for example,* ***perfluorooctane sulfonate****). Different naming conventions in laboratory reports have led to confusion regarding exactly which form of the PFAA the labs are measuring. Although the lab is measuring the concentration of PFAA anions present in the sample, where the results are reported as an acid, the lab has adjusted for the H+ cation (which has so little mass, this does not affect the resulting concentration). It should be noted that the standards used by laboratories to perform analyses may be prepared from PFAA salts, as is often the case for sulfonate standards. If so, the lab must adjust the reported concentration to account for the mass of the counterion (typical Na+ or K+). The calculation to do this is described in section 7.2.3 of EPA Method 537 (USEPA 2009[794]).*

2.2.3.2 Perfluoroalkane Sulfonamides (FASAs)

FASAs, such as perfluorooctane sulfonamide (FOSA), are products and/or intermediates from the ECF process for surfactants and surface protection products. FASAs can transform to form PFAAs such as PFOS.

2.2.3.3 Other Perfluoroalkyl Substances

Other perfluoroalkyl substances shown on Figure 2-4 and Figure 2-5 include:

- perfluoroalkane sulfonyl fluorides [PASFs, such as perfluorooctane sulfonyl fluoride (POSF) and perfluorobutane sulfonyl fluoride (PBSF)], and perfluoroalkanoyl fluorides (PAFs), associated with the ECF process
- perfluoroalkyl iodides (PFAIs) and perfluoroalkane aldehydes (PFALs), associated with the fluorotelomerization process
- perfluoroalkyl ether acids, including perfluoroalkyl ether carboxylic acids (PFECAs) and perfluoroalkyl ether sulfonic acids (PFESAs)

As discussed in Section 2.4, some PFECAs have been developed or used as replacements for other PFAS that are phased out of production and use. This includes GenX chemicals (see text box). Other emerging fluorinated replacement PFECAs more recently detected in the environment, such as perfluoro-2-methoxyacetic acid (PFMOAA), are described in Sun et al. (2016).

GenX Chemicals

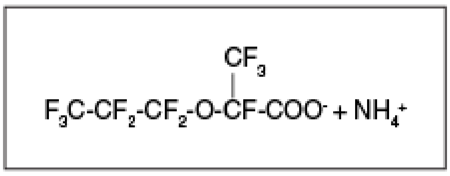
A PFECA, commonly referred to by the trade name "GenX," has been used by one manufacturer as a replacement for APFO (PFOA) as a surfactant and polymerization aid in the production of their PTFE product. GenX actually refers to the GenX processing aid technology, while the major chemicals used include:

- hexafluoropropylene oxide (HFPO) dimer acid (HFPO-DA, CAS No. 13252-13-6, also known as 2,3,3,3-tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)propanoic acid [PFPrOPrA] or FRD-903) and
- its ammonium salt (ammonium, 2,3,3,3- tetrafluoro-2-(heptafluoropropoxy) propanoate [$CF_3CF_2CF_2OCF(CF_3)COO^-NH_4^+$, CAS No. 62037-80-3, also known as FRD -902])

(Wang et al. 2013; Buck 2015; USEPA 2018).

Prior to their use in PTFE production, GenX chemicals were produced as a byproduct of other manufacturing processes (NC DEQ 2018). From the GenX Toxicity Assessment document by USEPA (2022), HFPO also is used to manufacture other HFPO-DA derivatives, fluoropolymers and perfluoropolyethers, and other specialty agrochemical, semiconductor, and pharmaceutical applications. HFPO-trimer acid and longer polymer fluorides can be formed from reaction of HFPO-DA.

Further discussion of the GenX chemicals is provided in Section 2.4.6. The chemical structure of the ammonium salt is shown in Figure 2-9.



$F_3C\text{-}CF_2\text{-}CF_2\text{-}O\text{-}\overset{CF_3}{\overset{|}{C}}F\text{-}COO^- + NH_4^+$

Figure 2-9. Example replacement chemistry structure for GenX Ammonium Salt.

In addition to linear and branched structures, certain cyclic structures have much in common with the noncyclic PFAS and are consistent with the definitions/descriptions provided above. As an example, Figure 2-10 illustrates the structure of perfluoro-4-ethylcyclohexanesulfonate, also perfluoro-p-ethylcyclohexylsulfonic acid (PFECHS), which some classify as a PFAS (MPART 2020). It is used in airplane hydraulic fluids and has been found both in the environment (Kaboré et al. 2018; Howard and Muir 2010; De Silva et al. 2011; Lescord et al. 2015; Houde et al. 2016) and in human blood (Miaz et al. 2020). The characteristics of PFECHS include:

- fully fluorinated six-carbon ring
- nonaromatic
- sulfonate active group
- perfluorinated two-carbon tail

PFECHS fits the Buck et al. (2011) description by having a fully fluorinated aliphatic tail of one or more carbon atoms attached to a charged functional group head.

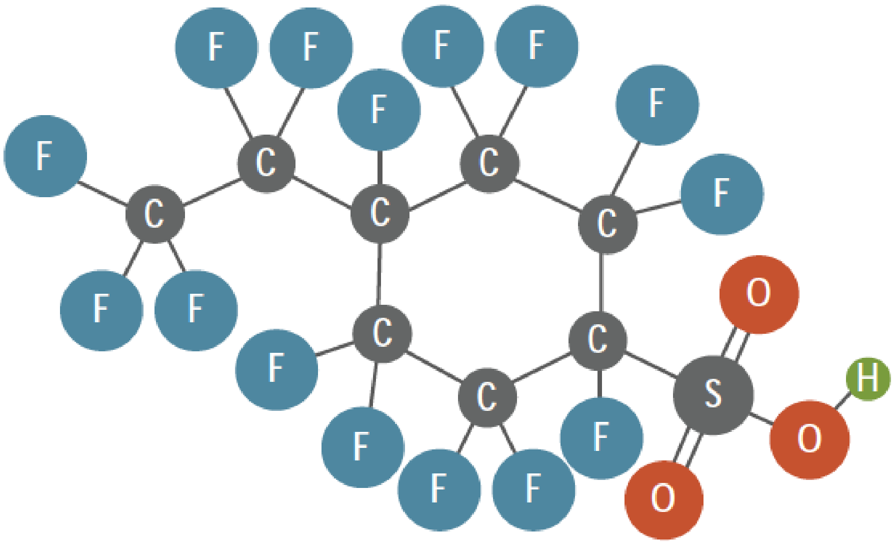


Figure 2-10. Illustration of perfluoro-p-ethylcyclohexyl sulfonic acid structure.

Source: M.Olson, Trihydro. Used with permission.

2.2.4 Polyfluoroalkyl Substances

Polyfluoroalkyl substances including some side-chain fluorinated polymers are increasingly being identified as important to understanding the occurrence, fate, and transport of PFAS at release sites and in the environment (OECD 2013; Butt, Muir, and Mabury 2014; Liu and Mejia-Avendaño 2013; Wang et al. 2011; Mejia-Avendaño et al. 2020). Figure 2-4 and Figure 2-5 highlight the groups of polyfluoroalkyl substances that, to date, have most commonly been detected at PFAS sites (see Barzen-Hanson et al. 2017; OECD 2018). Of the approximately 4,700 PFAS identified in the OECD (2018) study, about 90% were potential precursors to PFAAs.

Polyfluoroalkyl substances are distinguished from perfluoroalkyl substances by not being fully fluorinated. Instead, they are aliphatic substances for which all hydrogen atoms attached to at least one (but not all) carbon atoms have been replaced by fluorine atoms, in such a manner that they contain the perfluoroalkyl moiety CnF2n+1 (Buck et al. 2011), see Figure 2-6.

The carbon-hydrogen (or other nonfluorinated) bond in polyfluoroalkyl molecules creates a “weak” point in the carbon chain that may be susceptible to biotic or abiotic transformation. As a result, many polyfluoroalkyl substances that contain a perfluoroalkyl CnF2n+1 moiety are potential precursor compounds that have the potential to be transformed into PFAAs.

Figure 2-11 provides examples of transformation pathways for environmentally relevant polyfluoroalkyl precursors derived from two PFAS production methods, fluorotelomerization and ECF, respectively (Buck et al. 2011; Liu and Mejia-Avendaño 2013; Butt, Muir, and Mabury 2014; Martin et al. 2006). Note that these figures include some PFAS not discussed in this guidance document, but described in Buck et al. (2011). Refer to Section 5.4 for further information on transformation processes, noting that not all transformation products will be formed through every environmental transformation process.

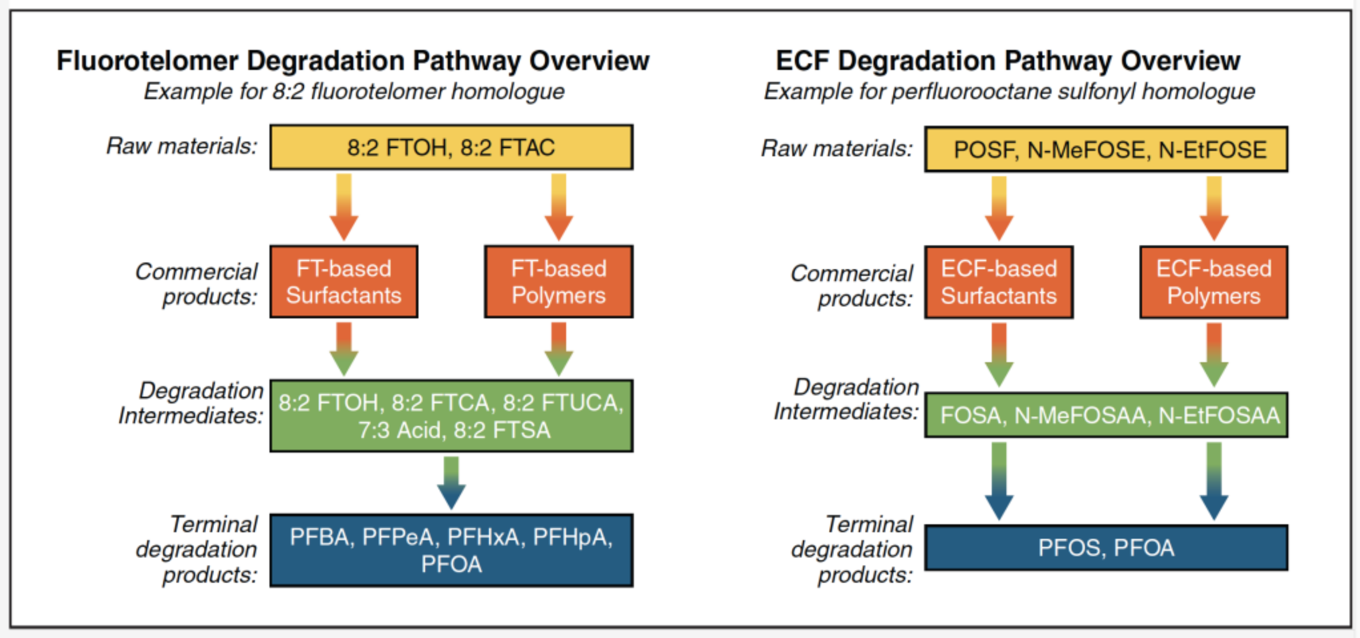


Figure 2-11. Example polyfluoroalkyl substance **transformation pathways.**

(Note that transformation of POSF-based products is for the terrestrial environment, but transformation into lower homologues of PFCAs and PFSAs in the atmosphere is also possible, see references in the paragraph above.)

2.2.4.1 Fluorotelomer *Substances*

Fluorotelomer substances are polyfluoroalkyl substances produced by the fluorotelomerization process. As shown in Figure 2-11, the transformation of fluorotelomer-based substances is a potential source of PFCAs in the environment, but not PFSAs (Buck et al. 2011).

Fluorotelomer-based polyfluoroalkyl substances are named using an “n:x” prefix where “n” indicates the number of fully fluorinated carbon atoms (n > 2) and “x” indicates the number of carbon atoms that are not fully fluorinated (x > 1). An example of a polyfluoroalkyl substance is shown in Figure 2-12, which also illustrates the “n:x” naming convention.

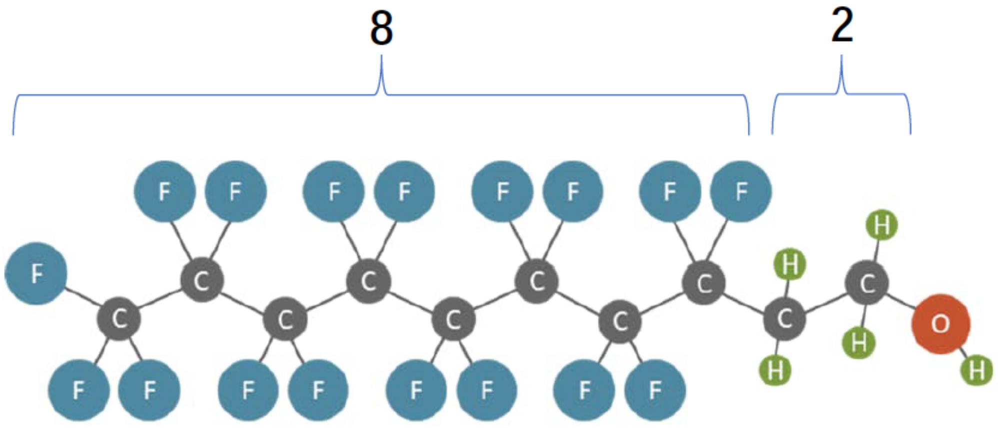


Figure 2-12. Example of a polyfluoroalkyl substance.

Source: M. Olson, Trihydro. Used with permission.

Some of the fluorotelomer substances most commonly detected in the environment to date are as follows (Section 6):

- *Fluorotelomer alcohols* (FTOH): The n:2 fluorotelomer alcohols (n:2 FTOHs) are key raw materials in the production of n:2 fluorotelomer acrylates and n:2 fluorotelomer methacrylates (Buck et al. 2011).
- *Fluorotelomer sulfonic acids* (FTS): The n:2 fluorotelomer sulfonic acids (n:2 FTSs) have been detected in environmental matrices at sites where aqueous film-forming foam (AFFF) has been used, and also in wastewater treatment plant effluents and landfill leachate. FTSs are precursor compounds and can undergo aerobic biotransformation to form PFCAs (Buck et al. 2011).
- *Fluorotelomer carboxylic acids* (FTCA): These compounds form through the biotransformation of FTOHs (Figure 2-11; (Buck et al. 2011; Mejia-Avendaño et al. 2016) and have been detected in landfill leachate. Note that the –COOH functional group on these fluorotelomer compounds means they may have either an even or odd number of carbons, so they may have n:2 or n:3 prefixes.

Other fluorotelomer (FT) substances are shown in Figure 2-6.

2.2.4.2 Perfluoroalkane Sulfonamido Substances

The subgroups of perfluoroalkane sulfonamido substances shown in Figure 2-5 and discussed below have been detected in the environment and humans (Buck et al. 2011). Perfluoroalkane refers to the fully fluorinated carbon chain tail, but these compounds also contain one or more CH2 groups in the head of the molecule attached to the sulfonamido spacer (Figure 2-13). They are either used as raw materials for surfactant and surface treatment products, or they are present as intermediate transformation products of these raw materials. As shown in the transformation pathways in Figure 2-11, some perfluoroalkane sulfonamido substances have been found to transform to PFOS (Mejia-Avendaño and Liu 2015). Environmentally relevant perfluoroalkane sulfonamido substances include:

- *N-Alkyl perfluoroalkane sulfonamides* (N-alkyl FASAs) are raw materials used for surfactant and surface treatment products that include N-methyl perfluorooctane sulfonamide (N-MeFOSA) and N-ethyl perfluorooctane sulfonamide (N-EtFOSA) (Buck et al. 2011)
- *Perfluoroalkane sulfonamido ethanols* (FASEs) and *N-alkyl perfluoroalkane sulfonamido ethanols* (N-MeFASEs, N-EtFASEs, N-BuFASEs) are raw materials for surfactant and surface treatment products (Buck et al. 2011). Figure 2-13 illustrates the structure of N-EtFOSE
- *Perfluoroalkane sulfonamido acetic acids* (FASAAs) and *N-alkyl perfluoroalkane sulfonamido acetic acids* (N-MeFASAAs, N-EtFASAAs, N-BuFASAAs*)* are intermediate transformation products of FASEs, N-MeFASEs, N-EtFASEs, and N-BuFASEs (Figure 2-11) (Buck et al. 2011)
- *N-alkyl perfluoroalkane sulfonamidoethyl acrylates/methacrylates* (N-MeFAS(M)ACs, N-EtFAS(M)ACs, N-BuFAS(M)ACs)

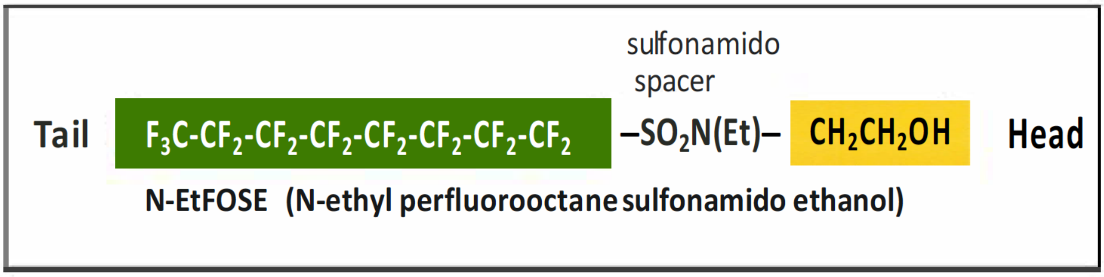


Figure 2-13. Example of a perfluoroalkane sulfonamido ethanol (FASE).

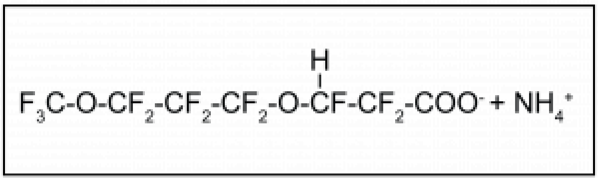
2.2.4.3 Other Polyfluoroalkyl Substances

Other polyfluoroalkyl substances shown in Figure 2-5 include:

- polyfluoroalkyl ether acids, including polyfluoroalkyl ether sulfonic acids (PFESAs) and polyfluoroalkyl ether carboxylic acids (PFECAs)
- chloropolyfluoroalkyl ether acids
- chloropolyfluoroalkyl acids

As discussed in Section 2.4.6, some PFAS have been developed or used as replacements for other PFAS that are phased out of use and production.

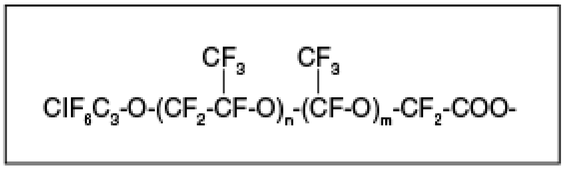
One replacement compound for the use of PFOA as a polymerization aid in the production of PTFE is a polyfluoroalkyl ether carboxylic acid: ammonium 4,8-dioxa-3H-perfluorononanoate (CF3OCF2CF2CF2-OCHFCF2COO–NH4+ (CAS No. 958445-44-8), commonly referred to by the trade name ADONA (Gordon 2011). The chemical structure is shown in Figure 2-14.



$$F_3C\text{-}O\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}O\text{-}\overset{\displaystyle H}{\overset{|}{C}}F\text{-}CF_2\text{-}COO^- + NH_4^+$$

Figure 2-14. Chemical structure for ADONA ammonium salt.

Other replacement polymerization compounds for the manufacture of PTFE and polyvinylidene fluoride (PVDF) include polyfluoroalkyl ether acids, also referred to as cyclic or polymeric functionalized perfluoropolyethers (PFPEs) (Wang et al. 2013). A sample chemical structure of a chloropolyfluoroalkyl ether acid is shown in Figure 2-15.



$$ClF_6C_3\text{-}O\text{-}(CF_2\text{-}\overset{\displaystyle CF_3}{\overset{|}{C}}F\text{-}O)_n\text{-}(\overset{\displaystyle CF_3}{\overset{|}{C}}F\text{-}O)_m\text{-}CF_2\text{-}COO\text{-}$$

Figure 2-15. Sample chemical structure for a chloropolyfluoroalkyl ether acid.

2.2.5 Chemical Manufacturing

To differentiate among PFAS in understanding a conceptual site model for environmental risk assessment, it is important to know about the chemical manufacturing processes. The various manufacturing processes produce different types of PFAS, such as linear and branched isomers (as discussed in this section), which may affect the environmental fate, treatment, toxicology, and site forensics for these chemicals. The type of PFAS that might be formed by the transformation of precursor PFAS at or related to an environmental release site also may depend on the manufacturing process (refer to the family tree in Figure 2-5).

2.2.5.1 Processes

Two major processes, *electrochemical fluorination (ECF)* and *fluorotelomerization*, have been (and are) used to manufacture PFAS that contain perfluoroalkyl chains: side-chain fluorinated polymers, PFAAs and polyfluoroalkyl surfactants (USEPA 2003; Benskin, DeSilva, and Martin 2010; KEMI 2015; OECD 2018). The fluorotelomerization process may also be characterized as "oligomerization," as it involves, for example, using tetrafluoroethylene (TFE) monomer and adding one to nine TFE monomers to form a perfluoroalkyl chain (Kissa 2001; Rao and Baker 1994). ECF and fluorotelomerization can be used to create some of the same PFAS, as shown on Figure 2-4. PFSAs are produced only using the ECF process, whereas PFCAs can be produced by both ECF and fluorotelomerization (USEPA 2003; CONCAWE 2016).

More than 600 intermediate processes have been used to further produce certain PFAS and the associated final products. Further discussion of the intermediate processes may be found in the general scientific literature and numerous textbooks specifically written about fluorinated organics and fluoropolymers (Banks, Smart, and Tatlow 1994).

Electrochemical Fluorination (ECF)

The Simons ECF process was licensed by 3M in 1945; 3M subsequently built an ECF pilot in 1949 and started commercial production in 1951 (3M Company 1999) In the ECF process, an electric current is passed through a solution of an organic feedstock and liquid anhydrous hydrogen fluoride, which causes the hydrogen atoms to be replaced by fluorine atoms, thereby creating carbon-fluorine bonds (3M Company 1999; USEPA 2003; Buck et al. 2011). ECF is used to create perfluoroalkane sulfonyl fluorides (PASFs), which are the building blocks for other sulfonyl-based PFAS, as well as perfluoroalkyl carboxylate derivatives. These ECF-synthesized PFAS can contain a variable mixture of linear and branched perfluorinated isomers, as well as other homologues, byproducts, and impurities (USEPA 2003; Buck et al. 2011). The variable composition is caused by the process conditions, raw materials, and equipment used by the ECF process (3M Company 1999; CONCAWE 2016). Subsequent processes (for example, hydrolysis, base neutralization) are then used to refine the compounds (USEPA 2003).

Historically, the ECF process was primarily used to produce POSF which was then used to make PFOS-based materials. PFOS is often a terminal transformation product of POSF-based compounds. ECF was also used to produce perfluorooctane carbonyl fluoride which was then used to produce PFOA and other derivatives (for example, using perfluorooctane carbonyl fluoride to produce PFOA and its salts, such as APFO). As part of the phaseout of production of select long-chain PFAS in the United States, 3M has ceased using ECF to make certain long-chain PFAS, such as POSF-based compounds (PFOS and PFHxS) and PFOA (Buck et al. 2011; Section 2.4.1). 3M's phaseout did not include other, shorter chain PFAS-based products, such as those based on PBSF (3M Company 2018).

Fluorotelomerization

A typical fluorotelomerization process involves the reaction of perfluoroethyl iodide (PFEI, CF_3CF_2-I) with tetrafluoroethylene (TFE, $CF_2{=}CF_2$) to yield a mixture of even-numbered carbon linear perfluoroalkyl iodides (C_nF_{2n+1}-I, n= 4, 6, 8, 10, etc.), commonly known as "Telomer A." Telomer A is then reacted with ethylene to make "Telomer B" (fluorotelomer iodide, $C_nF_{2n+1}CH_2CH_2$-I, n= 4, 6, 8, 10, etc.). Telomer B is reacted to make fluorotelomer alcohols (FTOHs, $C_nF_{2n+1}CH_2CH_2$-OH, n= 4, 6, 8,10, etc.) Telomer A, Telomer B, and FTOHs are the basic raw materials used to manufacture fluorotelomer-based surfactant (nonpolymer) and polymer products (Kissa 2001; Rao and Baker 1994).

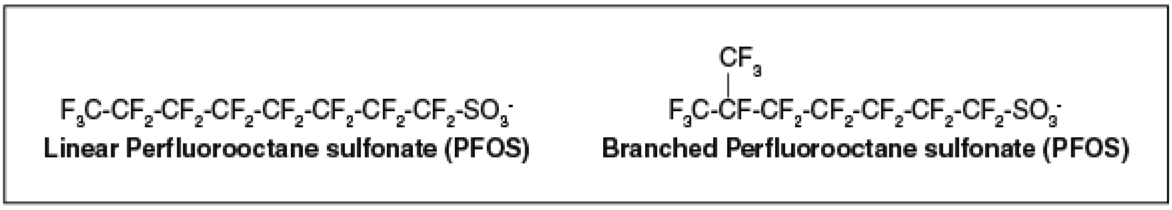
As part of the USEPA 2010/2015 Stewardship Program (USEPA 2018; Section 2.4.3), eight major global fluoropolymer and fluorotelomer manufacturers phased out production of long-chain fluorotelomer-based products that were potential precursors to PFOA and other long-chain perfluoroalkyl carboxylic acids (PFCAs). Today, the major global fluorotelomer manufacturers are reported to have refined their processes and predominantly manufacture short-chain (C6) fluorotelomer-based products (American Chemistry Council 2021). Some manufacturers outside of the United States (for example, China, India) have not phased out long-chain PFAS production (Song et al. 2018).

Fluorotelomerization has been primarily used to produce linear (straight-chain) PFAS isomers with an even number of carbon atoms (Buck et al. 2011), although some sources indicate that the process can also produce compounds with an odd number of carbons and branched chains (Lindstrom, Strynar, and Libelo 2011; Danish EPA 2015).

2.2.5.2 Linear *and Branched Isomers of PFAS*

Many PFAS may be present as mixtures of linear and branched isomers (Figure 2-16) depending on the manufacturing process that was used. These structural differences are important because they may affect how the compounds behave in the environment and may provide an indicator of their source. Structural differences are described below:

- A *linear isomer* is composed of carbon atoms bonded to only one or two carbons, which form a straight carbon backbone. There can be only one linear isomer in a Cn homologue (compounds with the same number of carbons in their tail) series.
- In a *branched isomer*, at least one carbon atom is bonded to more than two carbon atoms, which forms a branching of the carbon backbone. There can be many isomers per Cn homologue series.



$F_3C\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}SO_3^-$

Linear Perfluorooctane sulfonate (PFOS)

$F_3C\text{-}\overset{CF_3}{\overset{|}{C}}F\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}SO_3^-$

Branched Perfluorooctane sulfonate (PFOS)

Figure 2-16. Linear and one branched isomer of PFOS.

For simplicity, both linear and branched isomers are abbreviated using the same acronym in this document. Note that other nomenclature conventions further identify PFAS by labeling linear isomers (for example, n-PFOS) and branched isomers based on the location of the branch in the carbon chain (for example, 5m-PFOS) (Benskin, DeSilva, and Martin 2010).

The formula "C_nF_{2n+1}-" (where n is greater than or equal to 3) includes linear and branched structures. For example, PFOS and PFHxS are routinely present in environmental samples as a mixture of linear and branched isomers (Beesoon et al. 2011; Beesoon et al. 2012; Benskin, DeSilva, and Martin 2010).

Accurate quantification of PFAS that are mixtures of linear isomers and branched isomers in environmental matrices can be difficult (Riddell et al. 2009). However, the relative contributions of isomers may be useful in understanding sources of PFAS and the age of the source, because the production of isomers varies by manufacturing processes. For example, as discussed above, the fluorotelomerization process has been primarily used to produce mostly linear PFAAs, whereas the ECF process produces a mixture of linear and branched PFAA isomers (Table 2-4). Refer to Section 10.5 for more information on PFAS source identification. The presence of linear and branched isomers may also have implications for partitioning, transport, and bioaccumulation (Section 10.5.1.1).

Table 2-4. Manufacturing processes and potential PFAAs produced

Manufacturing Process	Commonly Found Polyfluorinated Substance (Precursors)	Potential PFAAs Produced
Fluorotelomerization	FTS[1]	Linear PFCAs[3]
	FTCA[2]	Linear PFCAs[3]
	FTOH	Linear PFCAs[3]
Electrochemical fluorination	FASE	Branched and linear PFCAs Branched and linear PFSAs
	FASAA	Branched and linear PFCAs Branched and linear PFSAs

[1] Fluorotelomer sulfonic acid: for example, may be found at AFFF sites

[2] Fluorotelomer carboxylic acids: for example, 5:3 FTCA may be found in landfill leachate

[3] Under certain instances, can produce mixture of linear and branched PFCAs

Updated September 2023.

2.3 Emerging Health and Environmental Concerns

Like other emerging contaminants, knowledge and concern about PFAS in the environment have evolved through a series of phases discussed in this section:

- discovery and/or synthesis of PFAS (Section 2.2.5), followed by growth in commercial production and use (Section 2.5)
- emerging health and environmental concerns, including:
  - awareness of potential health impacts (Section 2.3.1)
  - analytical developments (Section 2.3.2)
  - detection in the environment (Section 2.3.3)
  - growing awareness and concern (Section 2.3.4)
- subsequent efforts to reduce use of contaminants of concern and/or replace the contaminants of concern with alternate technologies and chemicals, accompanied by health and environmental questions about those chemicals (Section 2.4)

2.3.1 Awareness of Potential Health Impacts

Occupational studies in the 1970s found detections of some PFAS in the blood of exposed workers, and further studies in the 1990s reported detections in the blood of the general human population (Buck et al. 2011). In recent years, the presence of several long-chain PFAAs (PFOA, PFOS, PFNA, and PFHxS) have been measured in the low parts per billion (ppb, equivalent to nanograms per milliliter (ng/ml)) range in the blood serum of almost all residents of the United States and other industrialized nations (Kato and Calafat 2015; CDC 2022). These PFAS are present whether or not people were exposed in the workplace, likely due to the widespread use of PFAS in consumer products and industries (Kannan et al. 2004; Kärrman et al. 2006; Olsen et al. 2003). However, there have been decreasing concentrations of long-chain PFAAs in people’s blood serum, likely due to the voluntary reductions in production, especially PFOA and PFOS; refer to the CDC data presented below. Further information and discussion of studies and human health effects can be found in Section 7.1.

These findings led to increased awareness of PFAAs in the environment, associated human exposure, and the potential for health effects. Occupational workers may be more highly exposed, and at risk, than other populations (ATSDR 2018). Laboratory studies using animals and epidemiological studies of human populations show that exposure to some PFAS may be associated with a wide range of adverse human health effects (USEPA 2016; USEPA 2016; ASTDR 2021). Toxicity studies have mostly focused on PFOS and PFOA, as well as some other long-chain PFAAs (Section 7.1). More recently, the toxicology of other PFAS, such as fluorotelomers and shorter chain PFAAs, as well as replacement PFAS chemicals (such as GenX chemicals, Section 2.4.6), have received increased attention (CONCAWE 2016; USEPA 2016; USEPA 2021).

Unit	Mass per liter (L)	Mass per milliliter (mL)
1 part per million (ppm)	1 mg/L	1 µg/mL
1 part per billion (ppb)	1 µg/L	1 ng/mL
1 part per trillion (ppt)	1 ng/L	1 pg/mL

mg = milligrams, µg = micrograms, ng = nanograms, pg = picograms

1 ppm = 1,000 ppb = 1,000,000 ppt

ATSDR is undertaking a national, multi-site PFAS health study to evaluate the health impacts of PFAS in drinking water (ATSDR 2020). The study was authorized by the National Defense Authorization Acts of 2018 and 2019. According to ATSDR, “The information learned from the multi-site study will help all communities in the U.S. with PFAS exposures, including those that were not part of the study.” The multi-site health study builds on the Pease Health Study at former Pease Air Force Base in Newington, NH, which effectively serves as a pilot program. The health study is intended to provide a better understanding of the cause and effect relationship between PFAS at various concentration and specific health outcomes based on adults and children. The study is expected to improve upon epidemiological studies with limited information about exposure factors.

In addition to the PFAS health study, ATSDR conducted PFAS Exposure Assessments at 10 locations in the United States. The 10 locations selected had PFOA and PFOS in the public drinking water that had previously exceeded the EPA 2016 health advisory level of 70 ng/L and/or other state guidelines. Through the Exposure Assessments, ATSDR was able to estimate exposures to PFAS in these communities and compare those exposure estimates to measured levels in blood collected from participants. Results of these Exposure Assessments are published in ATSDR's Final Report (ATSDR 2022).

The Centers for Disease Control (CDC) has been including biomonitoring for specific PFAS in blood serum in its National Health and Nutrition Examination Survey (NHANES) surveys of the U.S. general population since 1999-2000, and the latest NHANES PFAS data are from 2017-18 (CDC 2022). Blood serum levels of some PFAS in NHANES monitoring have decreased over time, as shown in Figure 2-17.

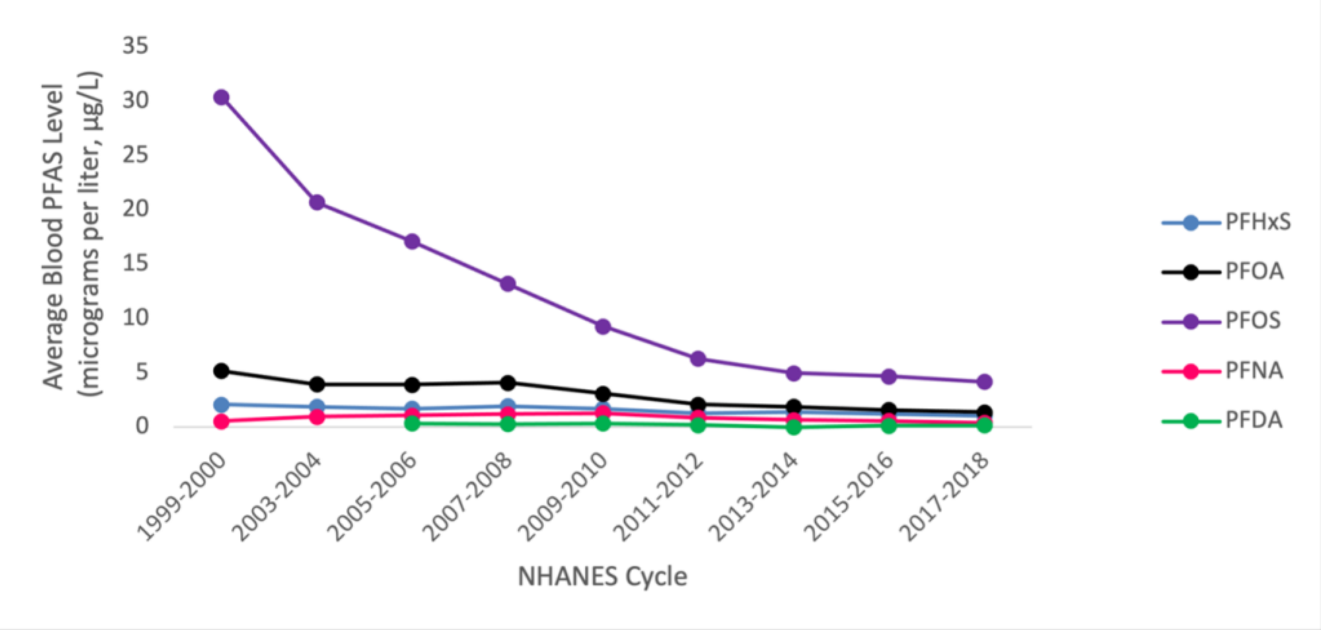


Figure 2-17. Blood Serum Levels of Specific PFAS Frequently Detected in the U.S. General Population (NHANES) Over Time (data from CDC 2022)

2.3.2 Analytical Developments

Early detection of PFAS in environmental media was hindered by the analytical capability challenges arising from the unique surface-active properties of PFAS (Giesy and Kannan 2001; 3M Company 2000). Since the 2000s, methods have been, and continue to be, developed with lower detection limits (for example, parts per trillion [ppt]) in water, that are commensurate with levels of potential human health effects. The number of commercial laboratories that offer PFAS analysis is increasing. Analytical methods continue to be developed and improved to test a variety of media and additional PFAS; these continue to improve our knowledge of PFAS in the environment and potential human health effects.

Since the early 2000s, three analytical methods have been developed, validated, and published by USEPA for the analysis of PFAS in drinking water. These include Methods 537, 537.1, and 533 (USEPA 2020). These methods were developed for finished drinking water from groundwater and surface water sources. According to USEPA, these methods were developed for accuracy, precision, and robustness and have been through multi-lab validation and peer review (see Section 11). USEPA notes that Method 537 was used extensively during Unregulated Contaminant Monitoring Rule 3, described above. In December 2019, USEPA published Method 533: Determination of Per- and Polyfluoroalkyl Substances in Drinking Water by Isotope Dilution Anion Exchange Solid Phase Extraction and Liquid Chromatography/Tandem Mass Spectrometry (USEPA 2019). While each method includes analytes not included in the other, the analytes targeted by Method 533 include shorter-chain PFAS and fluorotelomers (see Section 11.2.1.1). Methods 537.1 and 533 have both been validated for the analysis of HFPO-DA (a component of the GenX processing aid technology). The PFAS analytes associated with Methods 537.1 and 533 are listed in Table 2-5 (separate PDF) and categorized according to the family tree hierarchy. The USEPA has also published the draft USEPA Method 1633 that tests for up to 40 PFAS in eight environmental media (USEPA 2023). For further information on USEPA analytical methods, refer to Section 11.

The number of PFAS that can be identified and quantified by analysis has also evolved over time, with longer lists of compounds and changing commercial availability linked to evolving health and environmental concerns. Early focus was on PFOA and PFOS, but nationwide testing of drinking water supplies under the USEPA’s Third Unregulated Contaminant Monitoring Rule (UCMR3) led to four additional PFAAs (PFHpA, PFNA, PFBS, PFHxS) gaining greater attention. More information about UCMR3 is provided in Section 6.3, and a summary of the occurrence data for the six PFAAs analyzed during UCMR3 is provided in Section 8.2. UCMR5 is planned for in 2023–2025 and includes 29 PFAS using USEPA Methods 533 and 537.1. UCMR5 includes all large systems serving over 10,000 people, all small systems serving 3,300 to 10,000 people, and 800 randomly selected small systems serving less than 3,300 people (USEPA 2021).

Many state regulatory agencies now request or require testing for an expanded list of long- and short-chain PFAAs, and some potential precursors to PFAAs, such as fluorotelomers. Other polyfluoroalkyl substances are also receiving increased attention, as illustrated in Figure 2-18. Many of these PFAS are also summarized in Figure 2-6.

Other analytical methods and approaches are available to detect and quantify PFAS not included in the standard methods mentioned above, including nontarget analysis, total organic fluorine, and total oxidizable precursor assay (see Section 11).

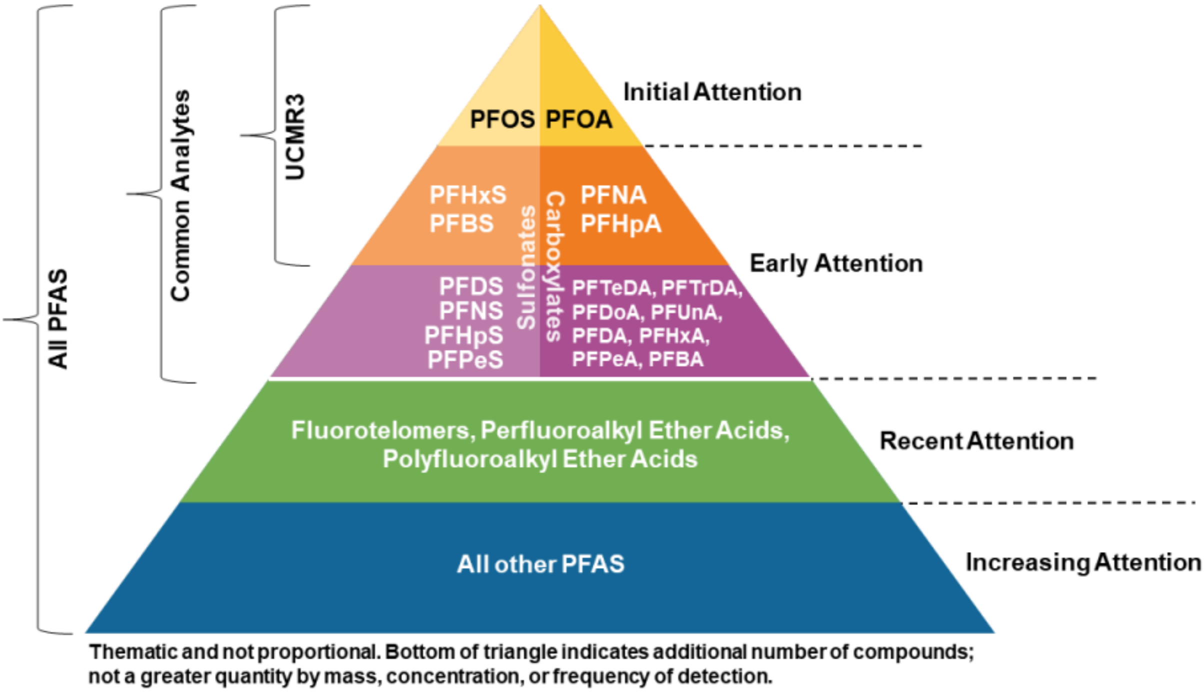


Figure 2-18. Emerging awareness and emphasis on PFAS occurrence in the environment

Source: J. Hale, Kleinfelder. Used with permission.

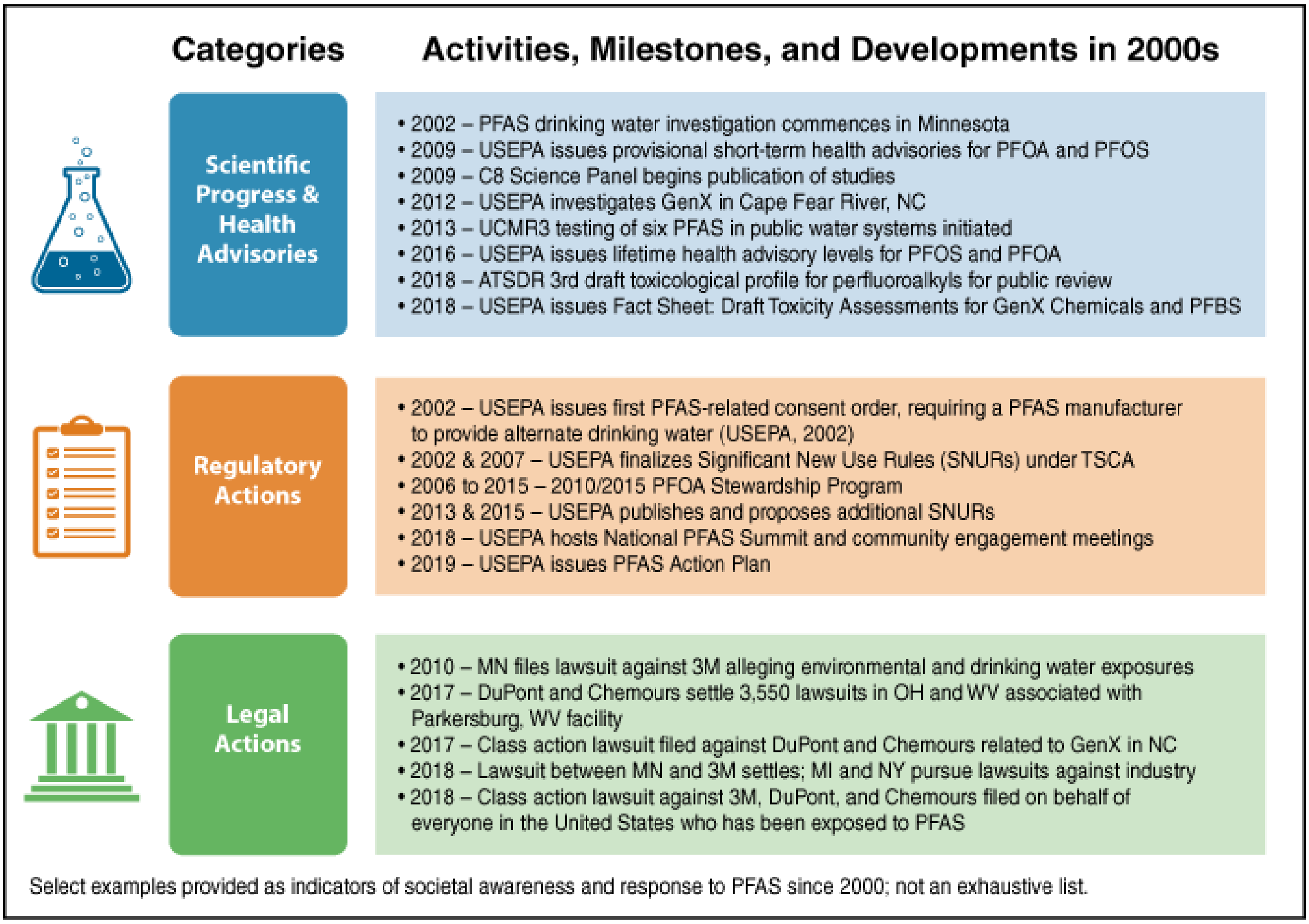
2.3.3 Detection in the Environment

Although some PFAS have been manufactured since the 1950s, PFAS were not widely documented in environmental samples until the early 2000s, as PFAS testing was not widely available until that time. Since the early 2000s, however, the occurrence of PFAS in the environment has been a very active area of research. The occurrence of certain PFAS has been reported in a wide variety of matrices, including sediments, surface and groundwater, and wildlife (Kannan et al. 2004; Yamashita et al. 2005; Higgins et al. 2007; Rankin et al. 2016). As noted above, UCMR3 sampling detected PFAS in 4% of drinking water supplies across the country, including in 33 states, three territories, and one Native American community (Hu et al. 2016). However, the Hu et al. study used a non-final download of the UCMR3 dataset, so final statistics may be different. Initially, investigations focused mainly on major releases from manufacturing sources and significant PFAS uses such as firefighting foam application sites.

In recent years, with more sensitive analytical methods available, studies have detected PFAS (especially PFAAs) in locations throughout the globe, even in areas well beyond where they were initially used or manufactured (Houde et al. 2011). Detections of certain PFAS in the environment in various media are detailed in Section 6, and ecological effects are described in Section 7.2.

2.3.4 Growing Awareness and Concern

Societal awareness and concern about PFAS have increased since regulatory activity began in the early 2000s. Societal awareness and response are documented in the form of scientific progress and health advisories, regulatory actions, and legal actions. Major milestones for these activities within the United States are summarized in Figure 2-19. Other milestones, such as the growth of knowledge and investigation at major manufacturing and DOD sites in various U.S. states, are not discussed here.



Categories	Activities, Milestones, and Developments in 2000s
Scientific Progress & Health Advisories	• 2002 – PFAS drinking water investigation commences in Minnesota • 2009 – USEPA issues provisional short-term health advisories for PFOA and PFOS • 2009 – C8 Science Panel begins publication of studies • 2012 – USEPA investigates GenX in Cape Fear River, NC • 2013 – UCMR3 testing of six PFAS in public water systems initiated • 2016 – USEPA issues lifetime health advisory levels for PFOS and PFOA • 2018 – ATSDR 3rd draft toxicological profile for perfluoroalkyls for public review • 2018 – USEPA issues Fact Sheet: Draft Toxicity Assessments for GenX Chemicals and PFBS
Regulatory Actions	• 2002 – USEPA issues first PFAS-related consent order, requiring a PFAS manufacturer to provide alternate drinking water (USEPA, 2002) • 2002 & 2007 – USEPA finalizes Significant New Use Rules (SNURs) under TSCA • 2006 to 2015 – 2010/2015 PFOA Stewardship Program • 2013 & 2015 – USEPA publishes and proposes additional SNURs • 2018 – USEPA hosts National PFAS Summit and community engagement meetings • 2019 – USEPA issues PFAS Action Plan
Legal Actions	• 2010 – MN files lawsuit against 3M alleging environmental and drinking water exposures • 2017 – DuPont and Chemours settle 3,550 lawsuits in OH and WV associated with Parkersburg, WV facility • 2017 – Class action lawsuit filed against DuPont and Chemours related to GenX in NC • 2018 – Lawsuit between MN and 3M settles; MI and NY pursue lawsuits against industry • 2018 – Class action lawsuit against 3M, DuPont, and Chemours filed on behalf of everyone in the United States who has been exposed to PFAS

Select examples provided as indicators of societal awareness and response to PFAS since 2000; not an exhaustive list.

Figure 2-19. Growing awareness and concern 2000-2019.

Updated September 2023.

2.4 PFAS Reductions and Alternative PFAS Formulations

Concern regarding the persistence, bioaccumulation, and possible ecological and human health effects of long-chain PFAAs has led manufacturers to use replacement PFAS chemistries, which include reformulating or substituting longer chain substances with generally shorter chain perfluoroalkyl or polyfluorinated substances that should not transform to long-chain PFAAs, or replacing manufacturing processes with nonfluorinated chemicals or alternate methods (USEPA 2006; OECD 2017). Manufacturing reductions and phaseouts are described in this section.

2.4.1 3M Voluntary Phaseout of Certain Long-Chain PFAS

In early 2000, 3M was the principal worldwide manufacturer of PFOA and POSF-derived PFAS (for example, PFOS) (Buck et al. 2011). This represented about 80–90% of global POSF-based production (Prevedouros et al. 2006), with 3M the sole U.S. manufacturer of PFOS (USEPA 2003). In 2000, 3M announced a voluntary, unilateral phaseout (this only applied to 3M) of POSF-derived PFAS, which at the time represented more than 95% of the company’s perfluorooctanyl production (3M Company 2000). The 3M phaseout included the six-, eight-, and ten-carbon PFSAs (PFHxS, PFOS, and PFDS) and related precursors, as well as PFOA (Buck et al., 2011). 3M reportedly completed most of the phaseout by the end of 2002, with the remaining phaseout completed by 2008 (USEPA 2017; 3M Company 2017).

At the time of the phaseout, 3M’s POSF-derived PFAS were used in several applications:

- ~41% for paper and packaging protectors
- ~36% for textiles, leather, and carpet treatment and fabric protectors
- ~19% as industrial surfactants, additives, and coatings (including electroplating and etching surfactants, household additives, insecticides, and other applications)
- ~3% in firefighting foam (3M Company 2000).

The paper and packaging protectors included POSF-based side-chain fluorinated polymers and phosphate diesters (Wang et al. 2013).

PFOA produced by 3M was primarily used as a fluoropolymer processing aid, with only about 3% of PFOA production used for other applications: mostly in antistatic coatings in medical films, with limited quantities used for electronics applications (for example, to create a humidity barrier on printed circuit boards and to coat precision bearings with silicone oil) (3M Company 2003).

This phaseout applied only to 3M, and only to select PFAS. 3M subsequently used (and reportedly continues to use) ECF to produce PBSF-based PFAS (for example, the four carbon PFSA: PFBS) (OECD 2013; Wang et al. 2015). Any new manufacture and/or import of the PFAS phased out by 3M requires USEPA review based on the Significant New Use Rules (SNURs) described in Section 2.4.2. Based on the 2012 Chemical Data Reporting effort, no company reported manufacture or import of PFOS into the United States (reporting was required for quantities greater than 25,000 pounds) (USEPA 2018).

When 3M stopped producing PFOA in the early 2000s, it is reported that the manufacture of PFOA was continued by other domestic and international producers using fluorotelomerization (USEPA 2003; Wang et al. 2014). Domestic PFOA production was later phased out by the eight major domestic producers, as described in Section 2.4.3. Global production is summarized in Section 2.4.4 and Section 2.4.5.

In December 2022, 3M issued a press release stating the company would discontinue the manufacturing of PFAS and the use of PFAS in its products by the end of 2025. This will include discontinuing the manufacturing of all fluoropolymers, fluorinated fluids, and PFAS-based additive products and the use of PFAS across their product portfolio.

2.4.2 USEPA Significant New Use Rules (SNURs)

In conjunction with these voluntary reductions and phase-outs, USEPA used its authority under the Toxic Substances Control Act (TSCA) to finalize SNURs between 2002 and 2020 to require notification to USEPA before any manufacture (including import) of select PFAS, which include, but are not limited to, some of the PFAS included in 3M's voluntary phaseout of PFOS and related chemicals (Section 2.4.1). The July 2020 SNUR restricts products containing certain PFAS that have been phased out from being imported into the United States (USEPA 2021). According to USEPA (2021), this SNUR levels the playing field for companies that had already voluntarily phased-out the use of long-chain PFAS under EPA's PFOA Stewardship Program. As of February 2023, 1,422 PFAS are on the TSCA Chemical Substance Inventory, a list of all existing chemical substances that are either currently or have historically been manufactured (including imported) or processed in the United States. Of these, 711 are considered "active" in commerce, meaning they were manufactured (including imported) or processed over the 10-year period ending June 21, 2016, or more recently. Updates to the TSCA inventory are published generally on a quarterly basis, including the number of chemicals on the "active" inventory (USEPA 2023). USEPA has reviewed more than 300 of the commercially active PFAS under the New Chemicals Program and regulated about 200 PFAS with consent orders and/or new chemical SNURs (USEPA 2021). A new proposed SNUR has been added regarding 300 PFAS that "have not been manufactured (including imported) or processed for many years and are consequently designated as inactive on the TSCA Chemical Substance Inventory" (USEPA 2023).

2.4.3 USEPA PFOA Stewardship Program

In January 2006, USEPA initiated the 2010/2015 PFOA Stewardship Program (USEPA 2006). Most PFOA produced in 2003 (around the time of the phaseout described in Section 2.4.1) was used as a processing aid in the manufacture of fluoropolymers, such as PTFE (USEPA 2003), and this was likely still the case at the time the stewardship program began.

The eight major manufacturing or processing companies that participated in the program are reportedly those that manufactured or processed the majority of these chemicals, including Arkema, Asahi, BASF Corporation (successor to Ciba), Clariant, Daikin, 3M/Dyneon, DuPont, and Solvay Solexis (USEPA 2018). There may be other manufacturing or processing companies that did not participate in the program (USEPA 2015). USEPA indicated that the eight participating companies successfully met the program goals, meeting a 95% reduction by 2010 in global facility emissions and product content, and eliminating production (100% reduction) of PFOA, certain longer chain PFCAs (higher homologues such as PFNA and PFDA), and related PFOA precursors (for example, 8:2 FTOH) by 2015 (USEPA 2017). Even though the program goals were met by the eight companies, the ongoing use of PFOA stock and imported materials has not been fully restricted (USEPA 2018). Products manufactured and imported prior to 2015, and materials with ongoing uses, may still contain these PFAS (USEPA 2018), and PFOA may be present as a trace contaminant in some other PFAS and fluoropolymer products (3M Company 2003). As discussed in Section 2.4.5, production is ongoing in other nations. Additional information on current US regulatory activities can be found in Section 8.2.

2.4.4 Stockholm Convention on Persistent Organic Pollutants

The Stockholm Convention on Persistent Organic Pollutants (POPs) is a United Nations treaty signed in 2001 aimed at reducing or eliminating the production, use, and release of key POPs. POPs are defined as synthetic, organic compounds that, to varying degrees, resist photolytic, biological, and chemical transformation (KEMI 2004, 2015; USEPA 2017). Chemicals listed as POPs satisfy screening criteria for persistence, bioaccumulation, long-range environmental transport, and adverse effects (Stockholm Convention 2001). The Stockholm Convention targets PFAS in these ways:

- In 2009, *Annex B of the Stockholm Convention* (which restricts production and use) was amended to include PFOS (and its salts and POSF), because it is persistent in the environment and is not known to transform at any environmental condition. Currently, the United States has not ratified the amendment (KEMI 2017). Annex B is not an outright ban; it allows certain approved uses and exemptions of POPs. Prior to 2019, approved, ongoing uses for PFOS under Annex B included select applications in photoimaging, semiconductor coatings and etching agents, metal plating, insect baits, chemically driven oil production, aviation hydraulic fluids, some medical devices, and color printer electronic parts (UNEP 2008, 2009).
- Additionally, the following amendments and recommendations have been made:
  - In May 2019, Annex B was amended to discontinue several of the previously allowed ongoing uses (UNEP 2019).
  - Annex A was amended in May 2019 to prohibit and/or eliminate the production and use of PFOA (its salts and PFOA-related compounds), with certain exemptions (UNEP 2019).

- the POPs Review Committee recommended in October 2019 to list PFHxS (and its salts and related compounds) in Annex A without specific exemptions (UNEP 2019)

2.4.5 Global Manufacture and Use of PFAS

PFAS are still manufactured globally, despite some PFAS (most notably PFOA and PFOS) no longer being produced in the United States, Europe, and Japan; for further information, see OECD's Country Information page on the OECD Portal on Per and Poly Fluorinated Chemicals (OECD 2017), "Risk Reduction Approaches for PFASs" (OECD 2015), and "Toward a New Comprehensive Global Database of Per- and Polyfluoroalkyl Substances" (OECD 2018). In addition to the domestic reductions discussed in Section 2.4.1 and 2.4.3, some of the phase-outs and restrictions are summarized below.

In 2017, the South Australia state government took initial steps to develop legislation banning environmentally harmful foams, such as Class B firefighting foams containing PFAS (SA EPA 2017).

Canada embarked on an Environmental Performance Agreement with four major manufacturers to phase out PFOA and related compounds from 2010 to 2015 (CEPA 2006). In 2008, Canada prohibited the use of most PFOS, with select exemptions such as use of existing stocks of PFOS-based firefighting foams, and then added PFOS to the Virtual Elimination List in 2009 and to the Prohibition of Certain Toxic Substances Regulations in 2016 (CEPA 2018). By 2016, Canada prohibited the import, manufacture, use and sale of PFOS, PFOA, and other long-chain PFCAs (and salts and precursors), with limited exemptions (CEPA 2018), and subsequently in 2018, Canada proposed further modification to those restrictions (Government of Canada 2018).

In 2009, the European Union (EU), through the European Chemicals Agency (ECHA), regulated PFOS as a POP, and use of PFOS is limited to certain restrictions (Vierke et al. 2012). In 2017, the EU banned the sale, use, and import of PFOA, its salts and PFOA-related substances through Annex XVII of the European Chemicals Regulation (REACH), with phase-outs occurring through 2032 and certain allowed uses. ECHA is currently considering restrictions for other long-chain PFCAs, their salts and precursors, as well as other compounds, such as PFHxA (ECHA 2018). On February 7, 2023, ECHA proposed restrictions on PFAS as a class; this proposal was prepared by Denmark, Germany, the Netherlands, Norway, and Sweden (ECHA 2023).

In Japan, there are restrictions on the manufacture, import, export, and use of PFOS and its salts (OECD 2015).

The global reduction anticipated with the U.S. phaseout of PFOA has potentially been offset by increased production of PFOA and related PFAS in China, India, and Russia (OECD 2015). PFAS manufacture began in China in the 1980s (World Bank 2017, 2017), and PFOS production in China increased coincident with the long-chain PFAA phaseout in the United States (CONCAWE 2016; OECD 2015). In 2016, PFOS and its derivatives were still being produced in Germany, Italy, and China (TTE 2016), but by early 2017, China was the only known producer of PFOS. China has ratified the Stockholm Convention on POPs and was awarded a grant from the Global Environment Facility (GEF) in 2017 to support the reduction of PFOS in China (World Bank 2017). China has developed some guidance for restriction and limitations of some PFAS (OECD 2015). In Brazil, EtFOSA, which is a precursor to FOSA and PFOS and used in the pesticide sulfluramid, which is still being produced on an industrial scale, is allowed as an approved use by the Stockholm Convention (Löfstedt Gilljam et al. 2016).

There does not appear to be a comprehensive reference publicly available to document the individual PFAS and the quantity of PFAS produced over the years. This is possibly because these data are proprietary or because quantities produced did not meet USEPA reporting requirements under TSCA, but could also be due to modifications to chemistries and products over the years (Lindstrom, Strynar, and Libelo 2011), complexity of the issue, and the general lack of publicly available data (OECD 2018). That said, some estimates of production and emissions of select PFAS have been made based on the limited available data.

Prevedouros et al. (2006) estimated global emission of PFCAs at about 3,500–8,000 tons between the 1950s and 2002, with approximately 80% of emissions related to fluoropolymer manufacture (and use), based on overall annual production estimates of:

- APFO (ammonium salt of PFOA)-about 335–525 tons per year between 1951 and 2002
- APFN (ammonium salt of PFNA)-about 60–225 tons per year between 1975 and 2004
- POSF (building block for PFOS)-about 9,550 tons per year from 1960 to 2002.

Other production and emissions estimates for PFCAs are available from OECD (2015) and Wang et al. (2014), and for PFOS and PFOS precursors from Armitage et al. (2009) and Paul, Jones, and Sweetman (2009). OECD (2015) called for a new, comprehensive survey to evaluate both historical and ongoing emissions.

2.4.6 PFAS-Based Replacement Chemistry

With the emerging awareness of potential health and environmental impacts of some PFAS and related limitations on production of some PFAS, such as the SNURs (Section 2.4.2) and 2010/2015 PFOA Stewardship Program (Section 2.4.3), manufacturers began efforts to replace the use of long-chain PFAS chemistries with nonfluorinated chemicals, alternate technologies, and/or other, shorter chain PFAS (Wang et al. 2013). For example, decorative chrome plating typically now uses less toxic chromium III instead of chromium VI so that PFAS are not needed (Wang et al. 2013).

Some of the replacement chemicals are said to achieve the same performance effectiveness of some of their predecessors. A carpet manufacturer has found that performance of fluorine-free alternatives is “equivalent or superior to the fluorinated treatments” pg. 66, (CalEPA 2018). Conversely, a 2015 study concluded that there are no nonfluorinated alternatives that provide equivalent technical performance in textiles (Danish EPA 2015). Refer to Section 3 for a discussion of PFAS-free AFFF that meets U.S. Department of Defense performance specifications.

Several studies suggest some of the alternate PFAS chemistries may or may not be less hazardous than the long-chain predecessors, although publicly available information on most replacement chemicals is limited (Wang et al. 2015 RIVM 2016; OECD 2015). Documentation regarding the USEPA’s review of hundreds of “shorter chain-length PFAS telomeric” substitutes is available under the TSCA New Chemicals Program (OECD 2013; USEPA 2017), and other documentation regarding replacement PFAS chemistries is available from the Performance Fluoropolymer Partnership (2021) and American Chemistry Council (2021). Draft toxicological evaluations have been provided for public comment by the USEPA for GenX chemicals and PFBS (USEPA 2018, 2018) with the PFBS Toxicity Assessment finalized in 2021 (USEPA 2021), and the GenX Toxicity Assessment finalized in 2021 as well (USEPA 2021) . For further discussion of toxicity documentation for select PFAAs and replacement chemistries, see Section 7.

Although a full discussion of such PFAS chemistries is not possible here, it is important to be aware of the trend toward shorter chain chemistries, as some of these PFAS increasingly may be detected in the environment. Some replacement PFAS have been detected in the environment and generated public concern and regulatory actions; however, information on significant environmental contamination by replacement PFAS is limited, and most are not detected by standard analytical methods (Wang et al. 2013). Some PFAS used as replacement chemicals, such as HFPO-DA and ADONA (used as replacements for APFO/PFOA in PTFE manufacture), and F-53B (11-Chloroeicosafluoro-3-1455 oxaundecane-1-sulfonic acid [11Cl-PF3OUdS or F-53B Minor], 9-Chlorohexadecafluoro-3-1456 oxanonane-1-sulfonic acid (9Cl-PF3ONS or F-53B Major]) (used as a replacement for PFOS in plating), have recently been added to USEPA Method 537.1 (USEPA 2018). Certain treatment processes used to remove these chemicals from waste streams may not be as effective as with longer chain PFAS (Sun et al. 2016).

Alternate PFAS chemistries are being used to replace long-chain PFAAs that have been phased out of production and/or use. In many cases, although similar legacy PFAAs were manufactured and used by many companies, these same companies have transitioned to the use of many different types of other PFAS as alternative chemicals. Many of these replacement PFAS are structurally similar to their long-chain predecessors, and are typically also manufactured using electrochemical fluorination (ECF) or fluorotelomerization (Wang et al. 2015; CONCAWE 2016). Some of these fluorinated substitutes may transform to form short-chain PFAAs. Some short-chain PFAAs, PFECAs (both per and poly), and related chemicals were manufactured as early as the 1980s, or earlier (Wang et al. 2015). Some PFAS used to replace long-chain PFAS are presented below (Hori et al. 2006; OECD 2007; Herzke, Olsson, and Posner 2012; Buck 2015; Wang et al. 2013; Wang et al. 2014; Wang et al. 2015; KEMI 2015; Sun et al. 2016; Holmquist et al. 2016):

- short chain homologues of the long-chain PFAAs, including PBSF-based derivatives (for example, 4-carbon chain PFBS in lieu of POSF-based six-, eight-, and ten-carbon chain compounds) in many applications, including surface treatment
- perfluorohexane sulfonyl fluoride (PHxSF, which can transform to PFHxS and is considered to be phased out in the United States) as an alternative to PFOS, primarily in China
- fluorotelomer-based products such as FTOH, for example, those with a six-carbon perfluorohexyl chain, including 6:2 fluorotelomer-based compounds in AFFF formulations and other six-carbon fluorotelomer-based products, side-chain fluorinated polymers, and PFPE products for surface treatment of food contact materials
- per- and poly-fluoroalkyl ether acids used as polymerization aids in manufacture of fluoropolymers, such as GenX chemicals (perfluoroalkyl ether acids) and ADONA (polyfluoroalkyl ether acids) used as a replacement for APFO in the manufacture of PTFE, as well as other types of perfluoroalkyl ether acids, also referred to as cyclic or

polymeric functionalized PFPEs as a replacement for APFN in the manufacture of polyvinylidene fluoride (PVDF)
- 6:2 fluorotelomer-based compounds, a PFBS-based compound, and PFAS known as F-53 and F-53B in lieu of PFOS in metal plating applications.

Updated September 2023.

2.5 PFAS Uses and Products

This section provides information on PFAS uses (Section 2.5.1), potential PFAS use or occurrence in some specific products (Section 2.5.2), and PFAS certifications (Section 2.5.3). Each section includes a table summarizing available information. The tables are not exhaustive.

2.5.1 PFAS Uses

PFAS have been produced on a commercial scale since the 1950s, and production continues today. The unique physical and chemical properties of PFAS impart oil, water, stain, and soil repellency, chemical and temperature resistance, friction reduction, and surfactant properties to a wide range of products, some of which are considered essential to health, safety, or modern life (Glüge et al. 2020). Glüge et al. (2020) categorized PFAS by uses according to industry application and practical use and identified more than 200 uses for more than 1,400 individual PFAS.

Table 2-6 provides a general (not exhaustive) introduction to some of the uses of PFAS chemistries that are, or have been, marketed or used (3M Company 1999; Poulsen et al. 2005; OECD 2006; Washington State Department of Ecology 2021; OECD 2011; OECD 2013; Fujii, Harada, and Koizumi 2013; OECD 2015; Performance Fluoropolymer Partnership 2021; Henry et al. 2018). The specific applications for all PFAS are not well documented in the public realm. For example, of the 2,000 PFAS identified in a 2015 study, only about half had an associated listed use (KEMI 2015). Further discussion of select uses that may be associated with potentially significant environmental releases are provided in Section 2.6.

As discussed in Section 2.2.2.1, most polymer PFAS are considered to pose relatively less risk to human health and the environment than some nonpolymer PFAS. For this reason, Table 2-6 distinguishes between these two major classes of PFAS and where they are used in various industries and products. Glüge et al. (2020) provided a detailed listing of PFAS by use category/subcategory, function, and properties; however, it is not organized according to polymer versus nonpolymer PFAS used in these instances.

The major industries and applications summarized in the table are described in more detail in Section 2.6.1.

Table 2-6. Sample historic and current uses of PFAS

Industry/Application	PFAS Type	Documented Use and Examples of Some PFAS
Aviation and Aerospace	Polymer	Mechanical components made of fluoropolymers (such as PTFE and PFA tubing, piping, seals, gaskets, cables, and insulators)
	Nonpolymers	Hydraulic fluid additives made from PFSA salts (such as PFOS at about 0.1%) to prevent evaporation, fires, and corrosion
Automotive	Polymer	Mechanical components made of fluoropolymers, including wiring and cable, fuel delivery tubing, seals, bearings, gaskets and lubricants, and some polymer coatings on carpets
	Nonpolymers	Surface treatment for textiles, upholsteries, carpets, leather and exterior surfaces
Biocides (Herbicides and Pesticides)	Polymer	None reported
	Nonpolymers	Active ingredients such as short-chain sulfonamides in plant growth regulators and herbicides, and EtFOSA (sulfluramid) in ant and termite baits; inert enhancing ingredients in pesticides; PFPAs and PFPiAs as anti-foaming agents in solutions

Industry/Application	PFAS Type	Documented Use and Examples of Some PFAS
Biotechnology	Polymer	Polymers used for reaction vessels, stirrers, and other components, filtration, and moisture barrier
	Nonpolymers	Cell cultivation by delivery of oxygen and other gases and ultrafiltration and microporous membranes to prevent bacterial growth.
Building and Construction	Polymer	Fluoropolymer membranes and coatings (such as PTFE, PVDF, and/or side-chain fluorinated polymers) in architectural materials (like fabrics, roofing membranes, metals, stone, tiles, concrete, radomes); adhesives, seals, caulks; additives in paints (for example, low- and no-VOC latex paints), varnishes, dyes, stains, sealants; surface treatment agent and laminates for conserving landmarks
	Nonpolymers	Additives in paints, coatings, and surface treatments (PASF- and fluorotelomer-based compounds, ammonium salt of PFHxA)
Cable and Wiring	Polymer	Coatings and jacketings made of fluoropolymers (such as PTFE and PVDF) for weathering, flame, and soil resistance, with cables used in many applications, including communication facilities, antennae, and computer networks
	Nonpolymers	None reported
Chemical Industry	Polymer	Fluoropolymers used to coat chemical tanks and pipes to enhance corrosion and high temperature resistance, as sealing and gasket materials for chemical processing, and for filtration media used in chemical manufacturing processes and emissions controls
	Nonpolymers	Fluoropolymer processing aids, stabilization and binder for certain chemicals, elimination of imperfections, and provide inert reaction media
Cosmetics/Personal Care Products	Polymer	Dental floss, toothpaste, dental creams, tooth powders, throat lozenges, chewing gums, sunscreens, cosmetics, and micro powders used in creams and lotions.
	Nonpolymers	Cosmetics, shampoos, nail polish, eye makeup, denture cleaners, eye drops, contact lenses, and others
Electronics	Polymer	Fluoropolymers (such as PVDF and PTFE) used in insulators, solder sleeves, printed circuit boards, cell phones, computers, speakers, and transducers
	Nonpolymers	Flame retardants for polycarbonate resin (such as the potassium salt of PFBS)
Energy	Polymer	Fluoropolymer films (such as FEP, PVDF) to cover solar panel collectors, electrolyte fuel cells, PTFE expansion joint materials for power plants, filtration of fly ash from stack emissions
	Nonpolymers	Fuel cell and battery electrolyte (such as the lithium salt of PFAAs)
Explosives, Propellants, Guns, and Ammunition	Polymer	Fluoropolymers (PTFE) applied to guns for lubrication and antidegradation during long term storage, tungsten-iron-fluoropolymer shot alloys (replacement for lead in hunting waterfowl and coots), fluoropolymer use in visual flares, warheads, incendiaries, and others
	Nonpolymers	PFCAs used in energetics, infrared flares, ignitor pyrolant, coating of reactive metallic powders, combustion behavior modification and other processes
Firefighting/Safety	Polymer	Fluoropolymers used in firefighting equipment and protective clothing (such as those woven with PTFE). Other polymer coatings using side-chain fluorinated polymers)
	Nonpolymers	Coatings and materials used as water repellents and some Class B foam (may contain PFCAs, PFSAs, and fluorotelomer-based derivatives), vapor suppression for flammable liquids (for example, gasoline storage)
Food Processing	Polymer	Fluoropolymer fabrication materials (such as PTFE) (liners for trays, ovens, grills)
	Nonpolymers	May be used as coatings on food packaging

Industry/Application	PFAS Type	Documented Use and Examples of Some PFAS
Household and Cleaning Products	Polymer	Nonstick coatings (fluoropolymers such as PTFE); aftermarket treatment for textiles, upholsteries, carpets, and leather (such as FT-based side-chain fluorinated polymers); sewing machine presser feet; glass
	Nonpolymers	Aftermarket treatment for textiles, upholsteries, carpets, and leather (such as PASFs; floor polishes (such as the ammonium salt of PFDA), coatings, and floor finishes (PFPAs and PFPiAs) and cleaning agents and alkaline cleaners; automobile waxes; may include PFAAs, PASF- and fluorotelomer-based derivatives, anti-reflective coatings, dry cleaning agent (PureDry®) replacement for Perc
Medical Products	Polymer	Fluoropolymers (such as PTFE) used in surgical patches, cardiovascular grafts, raw materials for human body implants (such as catheters, stents, sutures, device surface coatings, needles, and other) given biocompatibility and extremely low coefficient of friction, dialysis membranes, anesthesia, machine components (o-rings, filters, tubing, and other)
	Nonpolymers	X-ray film, stain- and water-repellent protective medical fabrics (like surgical drapes and gowns) created from PASF- or fluorotelomer-based (meth)acrylate polymers and polyurethanes, burn wound care cleaning product, oxygen and oxygen carriers used to improve therapeutic outcomes
Metal Plating	Polymer	None reported
	Nonpolymers	Wetting agent, mist suppression for harmful vapors, and surfactants (may include potassium, lithium, diethanolamine and ammonium salts of PFOS or 6:2 FTS)
Oil Production	Polymer	Lining of gas pipes
	Nonpolymers	Marketed for and potential instances of use in oil well production
Mining	Polymer	None reported
	Nonpolymers	Instances of surfactants used in ore mining flotation and leaching, improve separation of materials, and concentration of ore by destruction of mineral structure
Nuclear Industry	Polymer	Lubricants used for valves and centrifugal bearings in enrichment processes
	Nonpolymers	None reported
Oil and Gas Industry	Polymer	Lining of gas pipes and insulation of cable and wire during drilling, and membranes for filtration
	Nonpolymers	Marketed for and potential instances of use in oil well production to change the permeability of the target formation, reduce viscosity for transport, prevent evaporative loss during storage, tracers
Paper and Packaging	Polymer	Oil and grease and water repellent to paper, paperboard, molded pulp products (including food contact materials), and LDPE bags; examples include side-chain fluorinated polymers in which the PASF- or fluorotelomer-based alcohols or their acrylate or methacrylate esters are attached on side chains
	Nonpolymers	Phosphate ester salts (esterification of PASF or FT-based alcohols with phosphoric acid; PFPEs
Pharmaceutical Industry	Polymer	Polymers used for reaction vessels, stirrers, and other components, filtration, and moisture barrier
	Nonpolymers	Processing aids in the manufacture of microporous particles, additives and ingredients in certain types of medicine for drug delivery

Industry/Application	PFAS Type	Documented Use and Examples of Some PFAS
Photographic Industry	Polymer	None reported
	Nonpolymers	Photographic processing aids to reduce air bubbles and prevent foaming, wetting agents, stabilizers, and antistatic agents, prevent spots, and create uniform edge in multilayer coatings, anti-reflective agents
PFAS Production	Polymer	None reported
	Nonpolymers	Emulsion polymerization processing aids for fluoropolymers (such as PTFE, FEP, PFA, PVDF), (co)monomer of side-chain fluorinated polymers; (co)monomer of fluoropolymers and to make fluoroelastomers; may use salts of long-chain PFCAs (such as PFOA and PFNA), salts of short-chain PFCAs (such as PFHxA), or PFECAs
Photolithography & Semiconductor	Polymer	Equipment raw materials (such as PFA) for molded wafer baskets to handle corrosive liquids and gases, use as fluids in mechanical vacuum pumps
	Nonpolymers	Photolithography (such as using PFOS) in manufacture of semiconductor chips
Plastics and Rubber	Polymer	Fluoropolymers (such as PTFE) are used as processing aids, as a raw material in plastics and rubber production, and as an intermediate material. Used in molded material production to enable easy release and reduce imperfections, polymer processing aids
	Nonpolymers	Surface tension reduction for foams, etching of plastic, and production of rubber
Recreational and Musical Equipment	Polymer	Fluoro waxes used to reduce wear and abrasion on: stringed sports equipment (for example, tennis racquets) and stringed instruments; fishing rods and reels; lubricants; piano keys; ski wax
	Nonpolymers	None reported
Recycling and Material Recovery	Polymer	None reported
	Nonpolymers	Fluorosurfactants are used to recover metals, including rare earth metals, and n-hexane from waste gases
Refrigerants	Polymer	None reported
	Nonpolymers	Perfluorocarbons (PFCs), a subset of PFAS, used in refrigerant fluid and compressor systems for both heat transfer and lubrication
Textiles (Upholstery, Carpets), Leather, and Apparel	Polymer	Fluoropolymers (such as PTFE) are used in the construction of outdoor gear, clothing, and housewares; side-chain fluorinated polymers (such as PASF- or fluorotelomer-based (meth)acrylate polymers and -polyurethanes) may be used in oil- and water-repellent and stain release finishing and treatment coatings
	Nonpolymers	PFOA-based chromium treatment for paper and leather. Nonpolymer coatings used to treat textiles to provide oil- and water- repellent and stain release finishes
Wood Industry	Polymer	Polymeric PFAS fabric used during bleaching process, clear coating of wood substrate
	Nonpolymers	Adhesive resin on wood particle board

Information presented in this table captures potential instances of use but is not intended to indicate universal use. In addition, the table is not exhaustive of PFAS use in various industries.

2.5.2 Potential PFAS Use or Occurrence

Growing awareness of PFAS has led to both research and speculation about the use and occurrence of PFAS associated with an increasing number of consumer and commercial products, and whether such occurrences may constitute a risk to human health and the environment. Table 2-7 provides a high-level technical assessment of such recent claims, some of which have been popularized in the news media.

Table 2-7. Summary of Recent Claims of PFAS Use and Occurrence

Potential Use or Occurrence	**Technical Basis**	**Documentation**	**Conflicting Perceptions on Presence of PFAS and Significance of PFAS**
Cosmetics and Personal Care Products	Higher dermal absorption of PFOA from sunscreen than was previously reported for dermal absorption of PFOA: 1.6% of the applied dose was absorbed over time in a human volunteer.	Journal Articles, Abraham and Monien 2022; Whitehead et al. 2021, 2021	One study demonstrates significant uptake of a PFAA via transdermal absorption in humans may occur via PFOA mixed into sunscreen, indicating past occurrence of PFAS in some cosmetics may have contributed to this route of exposure. Other article discusses the use of PFAS in North American cosmetics to increase their durability and water resistance.
Face Masks	Chemical analysis of PFAS in face masks and calculations of leaching to landfill leachate.	Journal Article, Muensterman et al. 2022	Nine varieties of masks were tested. Homologous linear PFCAs and 6:2 FTOH indicated a fluorotelomer origin. Wearing masks treated with high levels of PFAS for extended periods can be a notable source of exposure with potential human health risk. Modeled annual disposal of ~29–91 billion masks assuming 100% leaching of individual PFAS into landfill leachate indicates mask disposal would contribute an additional 6% of annual PFAS mass loads and less than 11 kg of PFAS discharged to U.S. wastewater.
Fluorinated HDPE Containers	Testing of a limited number of fluorinated and non-fluorinated HDPE containers for presence of PFAS by EPA's Analytical Chemistry Laboratory at Fort Meade (initial and follow-up testing). Leaching of PFAS from container walls to liquid contents (methanol and water) was demonstrated for fluorinated containers. Degree of leaching relates to the brand of fluorinated containers and duration of liquid storage in container. Higher amounts of PFAS were detected in methanol solvent versus water.	USEPA Memos USEPA 2021; USEPA 2022	Through the fluorination process of HDPE containers, PFAS may be formed and then partly leach into the products inside the containers. These containers are believed to explain the occurrence of PFAS in mosquito control insecticide tested by an environmental group and published by news outlets.

Potential Use or Occurrence	Technical Basis	Documentation	Conflicting Perceptions on Presence of PFAS and Significance of PFAS
Food Packaging	Consumer Reports (CR) tested total organic fluorine content in multiple samples collected from 118 paper food packaging products from 24 restaurants and grocery chains. A subset of 50 products was tested by a method only identified as being "regularly used by industry, regulators, and researchers."	Consumer Reports, Loria 2022	The organic fluorine levels were averaged for each product. Thirty-seven products had an average organic fluorine concentration above 20 ppm, and 22 products had an average above 100 ppm. PFBA was found at the highest concentrations in the subset of 50 products analyzed by an alternate method.
Pesticides	Fluorinated pesticides may meet certain definitions of PFAS and therefore would be considered PFAS-containing.	Scientific American, Wilcox 2022	Article notes at least three active pesticide ingredients currently allowed by the USEPA—broflanilide, pyrifluquinazon and noviflumuron—meet its definition for a PFAS.
Pesticides	A university laboratory tested pesticide products. PFAS were detected in some of the products.	Lasee et al. 2022; USEPA 2023	USEPA's Analytical Chemistry Branch repeated the analyses for PFAS and conducted additional analyses. In USEPA's results no PFAS were detected above the method detection limits.

Potential Use or Occurrence	Technical Basis	Documentation	Conflicting Perceptions on Presence of PFAS and Significance of PFAS
Synthetic Turf	Media reports describe testing by non-profit organizations that detected PFOS on backing of older discarded turf material and 4 PFAS (PFOS, PFOA, PFHxS and 6:2-FTS) in nearby wetland water, 6:2 FTS on backing of newer turf material, and fluorine in 8 samples of grass blades acquired directly from distributors.	Fact Sheet, TURI 2020 CT DPH Review, CT DPH 2022 Lab analyses of PFAS in turf and wetland waters, Eurofins 2019 PEER Letter of Complaint to MassDEP, PEER 2019 Massey and Pollard 2023 City of Portsmouth, NH Evaluation of PFAS in Synthetic Turf, City of Portsmouth 2022 Project report, Tetra Tech 2021 Journal article, Lauria et al. 2022	Staff at Connecticut Department of Public Health (CT DPH) have retrieved and reviewed the original lab reports that were the basis of the media reports for PFAS detected in newer and older fields (and nearby wetland water) and determined that the available data do not provide scientific evidence that the detected PFAS originate from the artificial turf itself; their presence in turf may be attributable to other sources of PFAS, including sample contamination. The PFAS concentrations detected in turf and in nearby waterways are within the range of “background” levels of PFAS detected in soils in remote areas and in surface waters collected near urban areas. The Portsmouth, NH study evaluated analyses of synthetic turf samples utilizing standard PFAS analyses and TOP Assay; low-levels of select PFAS detected were determined to not represent a human health risk to users of the turf. Staff at CT DPH were unable to identify lab reports of the detection of fluorine in grass blades. Negligible PFAS leachate concentrations were also noted well below applicable criteria associated with synthetic turf at the Martha’s Vineyard Regional High School Athletic Fields. A study of artificial turf in Sweden determined that PFAS were detected intermittently and at low concentrations in backing (<LOD−0.63 ng of F/g; 71% DF) and filling (<LOD−0.15 ng of F/g; 18% DF) and were completely absent in blades. Studies reviewed did not show risk but not all manufacturers and products evaluated thus far.

2.5.3 PFAS Certification and Acceptability of Products

Numerous labels and certifications related to reduction or elimination of PFAS in products exist in the marketplace but there is great variation in the terms used to indicate PFAS content in products. Commonly used PFAS-related terms for products include: PFAS-free, PFOS-free, PFOA-free and Fluorine-free. However, many certifications allow a minimum limit to be present. The USEPA Sustainable Marketplace website (USEPA 2023) provides a useful compilation of PFAS-specific product certifications that lists the basis of the required and optional criteria. Many of the certifying organizations offer labels and criteria that may cover a wide range of chemicals and other sustainability considerations. The user should check the primary certifying organization’s documentation to verify their requirements for obtaining PFAS-specific certifications.

Table 2-8 provides examples of some of the most commonly-used product labels and certifications for intentionally-added PFAS. Several definitions exist for the term “intentionally added” in legislation and regulation. Examples of “intentionally added” definitions include:

- Maryland: H275/S273 “(C) Intentionally added means the act of deliberately using a chemical in the formation of a product where the chemicals continued presence is desired in the product to provide a specific characteristic.”

- Colorado: H1345(12) (a) Intentionally added PFAS chemicals" means a manufacturer has intentionally added has a functional or technical effect on the product. (b) includes intentional breakdown products of an added chemical."
- Hawaii: HB1644/S3000 "Intentionally introduced" means deliberately utilizing PFAS in the formulation of a package or packaging component where the continued presence of the PFAS is desired in the final package or packaging component to provide a specific characteristic, appearance, or quality."
- California: A2771 "(c) Intentionally added PFAS means either (1) PFAS chemicals that a manufacturer has intentionally added to a product and that have a functional or technical effect on the product; or (2) PFAS chemicals that are intentional breakdown products of an added chemical."

Many countries and states also have enacted individual bans for PFAS, or intentionally added PFAS, in products and some trade groups have developed product-specific certifications (for example, furniture, floor care products). Due to the dynamic and evolving nature of these labeling programs and requirements, users should consult the primary reference to get the most current information.

Certifications for unintentionally added PFAS have also been issued. The European Union's ECHA program requires that PFOA cannot exceed 25 ppb and PFOS cannot exceed 10 ppm as impurities (See Annex 1, Part A, European Union 2019).

Table 2-8. Examples of Certifications – Intentionally Added PFAS

Institution	**Products**	**Criteria**	**Reference**
USEPA Sustainable Marketplace	Comprehensive web site of multiple product categories	Links to multiple Standards and Ecolabel	https://www.epa.gov/greenerproducts/how-epas-recommended-standards-and-ecolabels-address-and-polyfluoroalkyl-substances
USEPA – Safer Choice	Industrial and consumer products	PFAS not specifically prohibited but EPA has determined that PFAS no longer meet the Safer Choice standard; **Exceptions** allowed; will be specifically called out as not meeting the standard in March of 2023 **Other** labels also listed	https://www.epa.gov/greenerproducts/how-epas-recommended-standards-and-ecolabels-address-and-polyfluoroalkyl-substances
FDA	Food-contact equipment & packaging	Authorized **limited** PFAS use for certain categories of food contact products	https://www.fda.gov/food/chemical-contaminants-food/authorized-uses-pfas-food-contact-applications
Green Screen	PFAS-free AFFF, cleaners and degreasers, furniture and fabrics, food service ware, and textiles	Separate limits for intentionally added PFAS **(0-100 ppm)** versus contamination as Total Organic Fluorine **(1-100 ppm)**, which vary by product category.	https://www.greenscreenchemicals.org/resources/entry/pfas-free-preferred-products

Institution	Products	Criteria	Reference
Biodegradable Products Institute (BPI)	Compostable products and packaging	No intentionally added PFAS; Limit of **100 ppm** total fluorine; SDS review; BPI-approved lab testing	https://bpiworld.org/fluorinated-chemicals https://www.epa.gov/greenerproducts/how-epas-recommended-standards-and-ecolabels-address-and-polyfluoroalkyl-substances
EWG	EWG-Verified Program for consumer products	Products cannot contain the PFAS that are on “Unacceptable” list of ingredients; Right to perform **random testing**	https://www.ewg.org/ewgverified/get-the-mark.php https://www.ewg.org/ewgverified/standards-cleaning.php
PFAS-Central	Referrals to PFAS-free products	Based on declared **company policy**, no independent verification	https://pfascentral.org/perch/resources/products/pfas-free-products-list-eligibility-one-pager.pdf

Updated September 2023.

2.6 PFAS Releases to the Environment

This section summarizes sources of PFAS releases to the environment that have the potential for significant environmental impact, based on the type and magnitude of the release, and the types and concentrations of PFAS associated with that release. These sources are sites where PFAS could be, or are known to have been, released to the environment, even if the site is not the location where the PFAS were generated or used. Refer to Section 2.1 for a discussion of the relative significance of releases and source control, as not all of these facilities will have, or have been documented to have, PFAS releases, and not all releases are of the same magnitude. “In the absence of high-quality testing data, PFAS contamination could be presumed” (Salvatore et al. 2022) at major sources and certain facilities as mentioned below. In addition, USEPA has developed an online database called the PFAS Analytic Tools that provides access to different sources of information about potential PFAS sources, drinking water sampling data, occurrence in environmental media, among others (USEPA 2023).

These major sources are located both in the United States and abroad, and include:

- industrial facilities that produce PFAS or process PFAS, or facilities that use PFAS chemicals or products in manufacturing or other activities (Section 2.6.1)
- areas where fluorine-containing Class B firefighting foams are stored, used, or released (Section 2.6.2)
- waste management facilities, such as landfills (Section 2.6.3)
- wastewater treatment residuals and areas of biosolids production and application, with more significant impacts associated with industrial wastewater discharges (Section 2.6.4).
- commercial inputs like schools, hotels, and box stores that can discharge high concentrations, linked to commercial cleaning activities like floor treatments (Section 2.6.1.7)

The fate and transport processes and distribution of PFAS in the environment are discussed in Section 5. Media-specific occurrence data are discussed in Section 6. Information about risk assessment, and human and ecological receptors is included in Section 9. Discussion of conceptual site model (CSM) components for each of the PFAS release categories listed above are included in Section 10.2.

2.6.1 Major Manufacturing and Industry Sources

Industrial source sites include primary and secondary manufacturing facilities. Primary manufacturing facilities are those where PFAS-containing products are synthesized and made into products or chemical feedstocks, or where PFAS are used as processing aids in fluoropolymer production. PFAS processing aids are not intended to be in the final product, but may be present at trace quantities (3M Company 2003; Buck et al. 2011).

Secondary manufacturing facilities may use fluoropolymers and PFAS-based materials produced at primary manufacturing facilities as part of industrial processes, such as the application of coatings to finished products. In some industrial settings, PFAS have been used for worker safety purposes, such as using 6:2 FTS or PFOS-based materials to suppress harmful mists during electroplating activities (Section 2.6.1.3).

USEPA (2021) includes PFAS manufacturers and PFAS formulators in the organic chemicals, plastics, and synthetic fibers (OCPSF) point source category, which includes a broad range of sectors, raw materials, and unit operations that may manufacture or use PFAS. PFAS manufacturers are defined as facilities that manufacture PFAS through electrochemical fluorination, fluorotelomerization, or other processes. PFAS formulators are defined as facilities that blend, convert, or integrate PFAS feedstocks with other materials to produce new commercial or intermediate products. USEPA (2021) identified six OCPSF PFAS manufacturing facilities and seven OCPSF PFAS formulators located in Illinois, Alabama, New Jersey, North Carolina, West Virginia, Minnesota, Pennsylvania, Ohio, Virginia, and Michigan.

PFAS composition and release mechanisms will vary for each facility. The composition of PFAS released from industrial facilities depends on the type of PFAS produced or used by the facility.

The general PFAS release mechanisms and pathways at industrial facilities are illustrated in CSM Figure 2-20 and include wastewater and stormwater discharges; on- and off-site disposal of solid wastes; accidental releases such as leaks and spills; and stack and fugitive emissions. Stack emissions may result in aerial deposition of PFAS to soil and surface water (with subsequent leaching and infiltration to groundwater) related to the facility (Davis et al. 2007; Shin et al. 2011), as well as short- and long-range air transport of PFAS. Industrial facilities may also contain areas where fire training or fire response using AFFF has occurred, AFFF storage areas, and AFFF fire suppression systems inside buildings. Like many AFFF release sites, industrial sites may also have releases of co-contaminants (solvents, petroleum products, etc.) that could potentially influence fate and transport of PFAS.

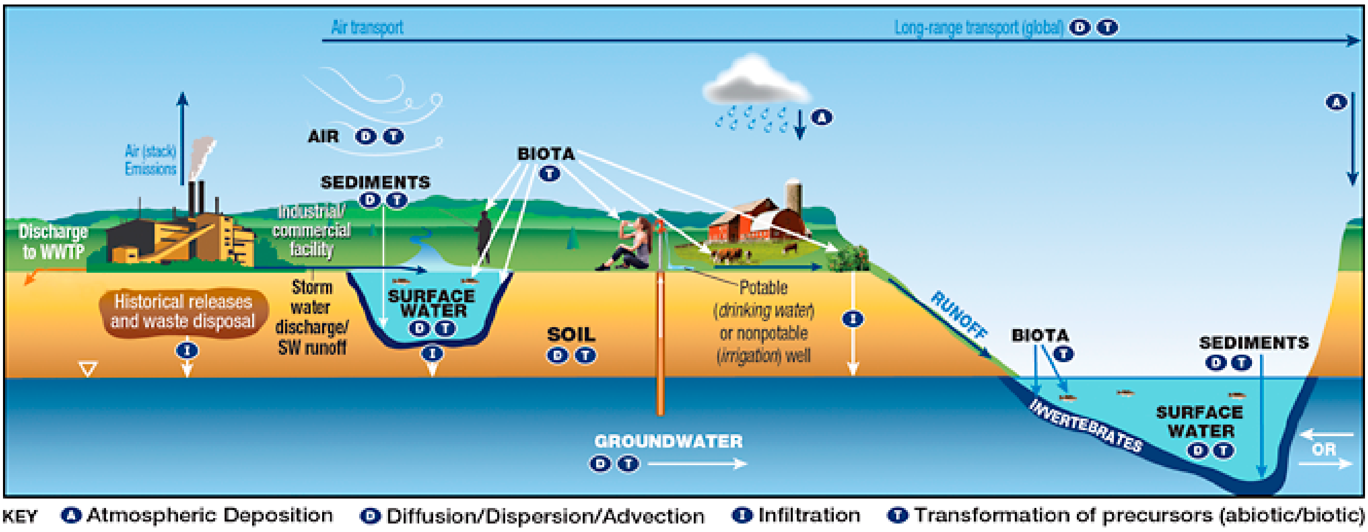


Figure 2-20. CSM for industrial sites.

Source: Adapted from figure by L. Trozzolo, TRC, used with permission.

The following subsections provide further details regarding potential sources of PFAS releases to the environment from PFAS use in manufacturing or industrial processes; these are not presented in order of the potential for significance of a release.

2.6.1.1 Building and Construction

Similar to other products, the chemical attributes of PFAS have led to advancements in building and construction materials. One particular application has been in composite wood and oriented strand board (OSB). Over the last 50 years, wood-based materials have used numerous additives for product strength and durability. A recent study performed on wood samples and OSB found primarily short-chain PFCAs and PFOA at concentrations ranging from 1.38 to 13.9 micrograms per kilogram (µg/kg) (Bečanová et al. 2016). Furthermore, wood fiber insulation has been shown to contain high amounts of PFHpA and other 5- to 8-carbon chain PFCAs (Bečanová et al. 2016). Many manufacturers use urea- or phenol-formaldehyde due to their performance and low cost; however, the composition of the resins used by many manufacturers is proprietary.

Other materials, including certain types of building insulation (phenolic foam) have shown high amounts of PFOS. Additionally, PFAS (predominantly C8–C20 gamma-omega-perfluorotelomer thiols with acrylamide) have been used in the production of lightweight concrete, concrete sandwich panels, and lightweight concrete blocks (Bečanová et al. 2016; Posner et al. 2013). The prevalence of these building materials in the construction of fire training areas, AFFF storage facilities, and other areas potentially exposed to PFAS led to potential issues with demolition waste. The porous nature of these materials (for example, concrete, brick) could lead to PFAS adsorption/absorption, representing a potential source of PFAS when disposed in landfills or recycling facilities (Australia Government DOD 2021).

PFAS, including fluoropolymers such as PTFE, are used in the manufacture of architectural fabrics, such as those used in the construction of roof domes, including large stadiums and transportation facilities (Performance Fluoropolymer Partnership 2021; Glüge et al. 2020).

PFOS-related chemicals have several uses in paint and varnishes. They can be used as wetting, leveling, and dispersing agents, and have also been used to improve gloss and antistatic properties. Additionally, they can be used as additives in dyestuff and ink. Furthermore, they can be used as pigment grinding aids or as agents to combat pigment flotation problems (KEMI 2004; RPA 2004). Fluorosurfactants are commonly used in coatings application for substrate wetting, leveling, reduction of surface tension, oil repellency, and dirt pickup resistance (Danish EPA 2015; Posner et al. 2013).

Information received from different suppliers within the paint and varnish industry suggests that fluorinated surfactants in general are much more expensive alternatives compared to other surfactants. Therefore, fluorosurfactants are used only for special purposes in paint and varnishes, where it is necessary to gain such a low surface tension that no other (nonfluorinated) alternatives can achieve (Danish EPA 2015).

Studies pertaining to PFAS in building materials continue to be published. The Green Science Policy Institute recently published a report that summarizes currently available studies for the purposes of informing those in the building and construction industry of the presence of PFAS and eliminating unnecessary uses (Fernandez, Kwiatkowski, and Bruton 2021).

2.6.1.2 Cable and Wiring

In the 1950s the wire and cable industry began to use extruded grades of PTFE. This is a suspension polymerization process, which does not require surfactants, unlike dispersion polymerizations (for example, Teflon-coated pans). Melt extrusion is the process by which most fluoropolymers are applied to wires. For instance, FEP, PFA, and PVDF are heated to 260°C and then melt extruded over wire to continuous lengths. The equipment used for melt-processable fluoropolymers requires temperature sensitivity of 427°F. PTFE is processed via paste extrusion for coating PTFE over wires due to its high melting point (ASTSWMO 2015; Kotthoff et al. 2015; Lau et al. 2007; Lindstrom, Strynar, and Libelo 2011; Oliaei et al. 2013; Renner 2001; Trudel et al. 2008). For more information on the safe handling of fluoropolymer resins during processing, see the Plastics Industry Association (2019) guidance document.

2.6.1.3 Metal Finishing and Plating

Electroplating is a process that uses electric current to apply a metal coating to the surface of an object. Metallic ions in an acidic electrolyte solution are used in the electrochemical deposition of metal coatings to the surface of the cathode (USEPA 1996).

PFAS, particularly PFOS, have been used as mist suppressants that are added to metal plating and finishing baths to prevent air emissions of toxic metal fumes. USEPA 2021 estimates that approximately half of the 1,339 chromium electroplating facilities in the United States still apply PFAS-based mist and fume suppressant. PFAS-containing chemicals may also be used in this industry as wetting agents, to reduce mechanical wear, and as surface coatings for reduced corrosion / enhanced appearance (USEPA 2021). Glüge et al. (2020) identified PFAS use in chrome, nickel, copper, tin, and zinc plating for lowering surface tension. In the United States, amendments to the National Emissions Standards for Hazardous Air Pollutants (NESHAP) under the Clean Air Act included a requirement to phase out the use of PFOS-based fume suppressants (a fume suppressant that contains 1% or greater PFOS by weight) in chromium electroplating by 2015 (USEPA 2012). Some countries (including the United States) have phased out the use of PFOS in some electroplating operations, adopting the use of other fluorotelomers (for example, 6:2 FTS) as a substitute in hard chrome plating operations (Danish EPA 2015; KEMI 2015) or changing decorative chrome plating operations to employ the less toxic trivalent chromium. PFAS known by the trade name F-53B have been used as metal plating mist suppressants in China (USEPA 2021; Bao et al. 2019). The toxicology of F-53B is reviewed in Section 17.2.6.1 (note that toxicological research may use different nomenclature for F-53B, namely 6:2 chlorinated polyfluoroether sulfonate (6:2 ClPFESA) and 8:2 ClPFESA (Munoz et al. 2019). Non-fluorinated fume suppressants are also now available.

Many different types of electroplating solutions can be used in plating activities, including hard and decorative chrome plating; chromic acid anodizing; nickel, cadmium, or lead plating; metal plating on plastics; and alkaline zinc plating. Chrome electroplating is the most significant contributor as it relates to PFAS use. In this process, PFAS are used as surfactants to reduce the surface tension of the electrolyte solution. Historically, PFOS was commonly used at a concentration of 5–10% to limit the development of bubbles and the emission of hexavalent chromium aerosols to workplace air, thereby reducing the potential hazard to workers posed by hexavalent chromium (USEPA 2009) (OSHA 2013) (Danish EPA 2015).

Studies show use of PFAS in these settings can result in high concentration wastewater discharges (USEPA 2009) and air emissions. Once the electrolyte solution can no longer be used, it may be treated to remove chromium and other metals, but PFOS and other PFAS may be present in effluent and deposited in sewage sludge (Danish EPA 2015). Investigations in Minnesota traced PFOS releases from one chrome plating operation to a wastewater treatment plant (WWTP) where elevated levels of PFOS were detected in the biosolids, effluent water, and fish in the receiving surface water (ATSDR 2008). Air emissions from another Minnesota chrome plater were found to have accumulated on the roof of the facility and from there contaminated stormwater and snow melting from the roof, which in turn contaminated the groundwater, a nearby surface water system, and fish (MPCA 2016). In another study in Minnesota looking at PFAS air and deposition monitoring, elevated PFAS were found in the vicinity of a chromium plater (MPCA 2022).

According to a study in Michigan by the Michigan Department of Environment, Great Lakes, and Energy (EGLE), 320 metal finishers that had a history of using fume suppressants were found to have PFOS in wastewater effluent. The report noted that 15% of metal finishers were discharging to WWTPs at concentrations greater than screening criteria (12 ppt PFOS) and 5% were discharging greater than 1,000 ppt PFOS (MI EGLE 2020). Of the metal finishers discharging PFOS above screening criteria, 89% used hexavalent and/or trivalent chromium in their current or past processes. Chrome platers in Michigan were determined to be in compliance with the NESHAP and many replaced PFOS with a fume suppressant containing 6:2 FTS. Some chrome platers did not use PFOS-containing chemicals to control fumes and have not been found to be sources of PFOS to WWTPs. Nearly half of the chrome platers regulated under the NESHAP used mechanisms other than chemical fume suppression. It was concluded that current effluent containing PFOS from facilities that have complied with NESHAP originates from historical use of PFOS-containing fume suppressants.

2.6.1.4 Industrial Surfactants and Fluoropolymer Production

PFAS have been, and currently are, instrumental as surfactants in industrial and commercial production. In the recent past, some information pertaining to specific surfactant uses of PFAS has become publicly available, though much information still remains unavailable. Most well documented is the historical use of PFOA as a processing aid in the manufacturing of PTFE, where APFO is used to help mix together the chemicals needed to combine units of tetrafluoroethylene (TFE) to make PTFE. Similarly, APFN, the ammonium salt of perfluorononanoic acid (PFNA), has also been used in the production of PVDF. PVDF polymers that are produced with the aid of APFN are sold in solid phase, with notable residual APFN concentrations (100–200 ppm) (Prevedouros et al. 2006).

Since the voluntary phaseout of PFOA and related PFAS chemistries, replacement chemistries such as ADONA and the GenX process chemicals are now used in the production of fluoropolymers.

The PFAAs used as polymerization aids may occur as impurities/residuals in some fluoropolymer products, as discussed in detail in Section 2.2.2.1

PFAS are also used in the manufacturing of plastics and fluoropolymers, rubber, and compression mold release coatings. These have applications in tubing, piping, drums, molds, and resins (Poulsen et al. 2005; Prevedouros et al. 2006).

2.6.1.5 Paper Products and Packaging

Since the 1960s, PFAS have been used as grease-proofing agents on food contact materials (FCM) to prevent oil, grease, and moisture from foods from leaking through the packaging. This includes coated paper and cardboard such as pizza boxes, microwavable popcorn bags, parchment paper, fast food wrappers, paper cups, pet food bags, and other items (Rao and Baker 1994; Hekster, Laane, and De Voogt 2003; Poulsen et al. 2005; Trudel et al. 2008; Buck et al. 2011).

The U.S. Food and Drug Administration (FDA) currently approves more than 90 unique monomer and polymer PFAS in FCMs (USFDA 2016). In January 2016, the FDA rescinded approval for three families of long-chain PFAS used in FCMs, but these had been voluntarily removed from the market in 2011. N-MeFOSE and N-EtFOSE were historically used to produce surface coatings for textiles and paper products (Zaggia and Ameduri 2012). PFAS currently used in FCM include polyfluorinated polyether-based polymers and shorter chain PFAAs (Wang, et al. 2015; Schaider et al. 2017). See Section 8.2 for additional information regarding a voluntary phaseout of 6:2 FTOH.

The most common PFAS detected in U.S. fast food wrappers include PFCAs (for example, PFOA and PFHxA), PFSAs (for example, PFBS), and fluorotelomer sulfonates (for example, 6:2 FTS) (Schaider et al. 2017). Six of 20 FCM tested were found to contain detectable levels of PFOA even though in 2011 U.S. manufacturers had voluntarily agreed to stop distributing FCM that were manufactured using PFOA via an FDA initiative. The methodology was not sensitive enough to detect if the PFAS were intentionally added to the packaging material or if they were attributed to unintentional background levels (Schaider et al. 2017). Refer also to Section 2.4.3 on the USEPA 2010/2015 PFOA Stewardship Program, which discusses the phaseout of PFOA and potential sources of PFOA that may remain in commercial and consumer products.

2.6.1.6 Photolithography/Semiconductor Industry

The semiconductor industry historically has used PFOS for their surface-active properties in the fabrication of imaging devices such as digital cameras, cell phones, printers, and scanners (Poulsen et al. 2005). Studies have shown semiconductor waste streams containing the PFAAs PFBS, PFHxS, PFOS, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnA, and PFDoA (Lin, Panchangam, and Lo 2009). Similarly, in photolithography processes, PFOS has been used predominantly in applying top-layer antireflective coatings (TARCs), bottom antireflective coatings (BARCs), and etchants. Smaller quantities of PFOS and longer-chain PFAS have been used in wet etchants, film developers, cleaners, protective coatings, and color filters (SIA 2008), with ongoing uses permitted (Section 2.4).

2.6.1.7 Textiles, Leather, and Apparel (Including Carpet and Furniture)

Surface treatment of textiles, leather, carpet, and furniture upholstery with PFAS to make them stain, oil, and water repellent occurs both before (that is, at the factory) and after consumer acquisition for ongoing stain, oil, and water repellency (Prevedouros et al. 2006; Ahrens 2011; Herzke, Olsson, and Posner 2012). Aftermarket PFAS-containing stain-repellent products for carpets allow consumers to treat carpets and textiles at home (Renner 2001; Hekster, Laane, and De Voogt 2003). Losses to the environment can be related to dry cleaning and laundering activities (Poulsen et al. 2005; 3M Company 2000).

Home textiles, including furniture and carpeting, as well as aftermarket PFAS surface treatment products, are also sources of long-chain perfluorinated chemical exposure (Guo et al. 2009). Textile coating operations may use water-emulsion or powdered feedstocks that contain greater proportions of PFCAs compared to PFSAs (Lassen et al. 2015; Gremmel, Frömel, and Knepper 2016). According to California EPA (CalEPA) CalEPA 2018, pg. 12, “The PFAS polymers used in carpets, rugs, and other textiles can contain various amounts of mobile residual raw materials, impurities, or transformation products, including PFAAs and other PFAA precursors such as fluorotelomer alcohols (FTOHs) and perfluoroalkyl sulfonamide alcohols.” Releases to the environment could occur from disposal of carpet cleaning wastewater (CalEPA 2018). Physical degradation of some consumer products (such as PFAS-treated textiles and carpets, as well as paper) may be a source of PFAS in house dust (Björklund, Thuresson, and de Wit 2009). The weathering of certain textiles can also be the causes of potential releases of PFAS (Schellenberger et al. 2022; van der Veen et al. 2020).

It should be noted that many treated home textiles and carpets are now manufactured with alternatives to long-chain PFAS; however, these products can have a long useful life, making it possible that items previously treated with long-chain PFAS are still in use (Brooke and Nwaogu 2004). A 2009 study of over 100 consumer products conducted by the USEPA and Arcadis indicated that pretreated carpet, treated upholstery and textiles, as well as other floor treatments, are likely the largest source of PFAS receptor exposure in American homes (Guo et al. 2009).

Other studies have since shown nonpolymeric PFAS in leather samples and outdoor textiles to impart water, oil and stain resistance; applications include protective clothing, outerwear, footwear, umbrellas, tents, and sails (OECD 2013; Walters and Santillo 2006; Kotthoff et al. 2015). Durable water repellent (DWR) is a fabric surface finish that creates a protective barrier. It is typically added at the factory, but is also available to consumers for apparel maintenance (Brooke and Nwaogu 2004). The finishes/treatments are applied to materials in mills/tanneries and as aftermarket applications by professionals or do-it-yourself consumers as aqueous dispersions. In some aftermarket applications, they are applied as solutions in hydrocarbon-based or halogenated solvents (OECD 2013).

2.6.1.8 Other Potential Commercial or Domestic Sources of PFAS Releases to the Environment

There is the potential for everyday uses of PFAS to result in relatively smaller releases of PFAS to the environment. Of note, these may include, but are not limited to leaching from materials to media (for example, well construction and plumbing materials), discharges to on-site wastewater disposal systems from use of household products and cosmetics, discharges from car washing and waxing, and use of ski waxes (professional ski wax technicians may have significant inhalation exposures to PFAS (Nilsson et al. 2013). Snowmelt and surface waters (Kwok et al. 2013), as well as snow, soil, and groundwater (Carlson and Tupper 2020), near ski areas may have measurable PFAS impacts.

2.6.2 Class B Fluorine-Containing Firefighting Foams

Some Class B firefighting foams designed for extinguishing flammable liquid hydrocarbon fires and vapor suppression may contain fluorine. These foams can be a major source of local PFAS release to the environment, with the CSM included in Figure 2-21.

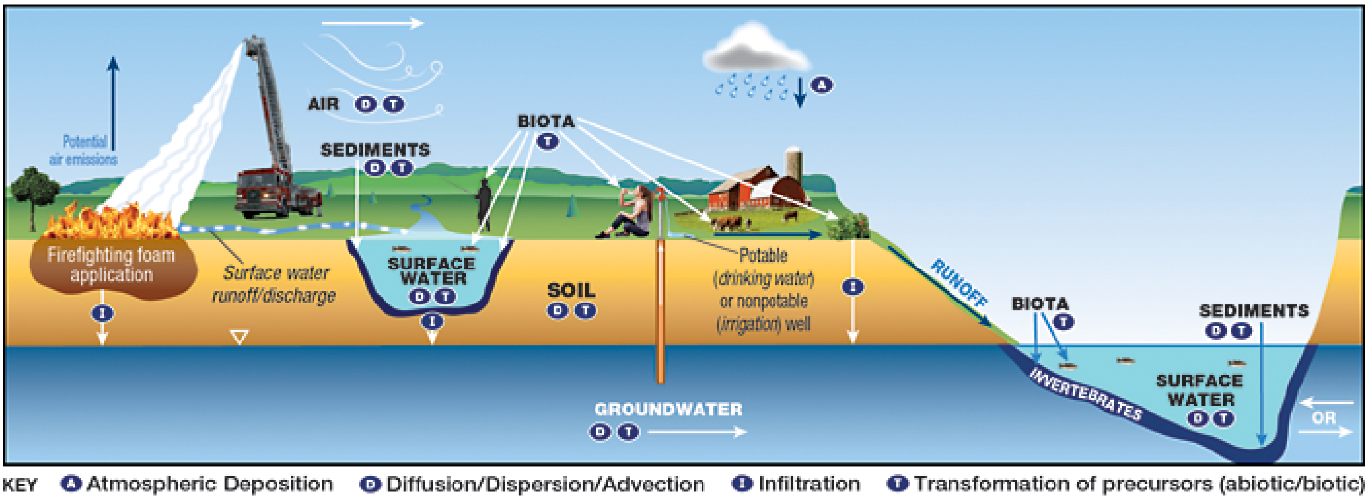


Figure 2-21. CSM for fire training areas.
Source: Adapted from figure by L. Trozzolo, TRC, used with permission.

Class B firefighting foams are commercial surfactant solutions that have been (and continue to be) stored and used for fire suppression, fire training, and flammable vapor suppression at military installations and civilian facilities and airports (Hu et al. 2016), as well as at petroleum refineries and bulk storage facilities, and chemical manufacturing plants and storage facilities (CONCAWE 2016). Additionally, local fire departments in communities have used and may maintain quantities of firefighting foam in their inventories for use in training and emergency response. Facilities that manufactured firefighting foams and landfills that received firefighting waste are also potential sources. Refer to Section 3 for more detailed information about firefighting foams.

2.6.3 Solid Waste Management Facilities

Environmental releases associated with the use of PFAS-containing products are primarily related to management of solid waste (for example, disposal of used items in a landfill or other legacy disposal areas). Other solid waste facilities, such as scrap yards and metal salvage facilities, might also be a potential source of release to the environment. Some PFAS are considered hazardous waste by some states (Section 8). Additional information pertaining to disposal of PFAS and PFAS-containing materials at MSW landfills can be found in the 2020 USEPA Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances (USEPA 2020).

Landfills can be sources of PFAS because they are the ultimate repositories for PFAS-contaminated industrial waste, sewage sludge from wastewater treatment facilities, and waste from site mitigation, as well as for PFAS-bearing consumer wastes, such as goods treated with hydrophobic, stain-resistant coatings (Busch et al. 2010; Eggen, Moeder, and Arukwe 2010). But the type and concentration of PFAS vary greatly among landfills, due to variations in the waste streams. Industrial waste can be a significant source of PFAS in landfills (as well as in wastewater and biosolids), particularly those that accept waste from facilities involved in the production or application of PFAS (Oliaei et al. 2013). Although MSW will contain PFAS due to its presence in so many consumer products, it generally is expected to have lower concentrations than landfills that accept industrial waste. Given the production timeline of PFAS, industrial, commercial, and consumer products and waste disposed since the 1950s are potential sources of PFAS release to the environment. As PFAS manufacturing processes change with time, the resulting type and composition of waste streams also change. PFAS production and use began several decades before the enactment of federal and state regulations governing waste disposal; as a consequence, environmental and drinking water impacts from disposal of legacy PFAS industrial and consumer waste have been documented (Oliaei, Kriens, and Weber 2010; Shin et al. 2011; MPCA 2017).

Figure 2-22 illustrates common elements of CSMs associated with the potential release scenarios at waste management facilities.

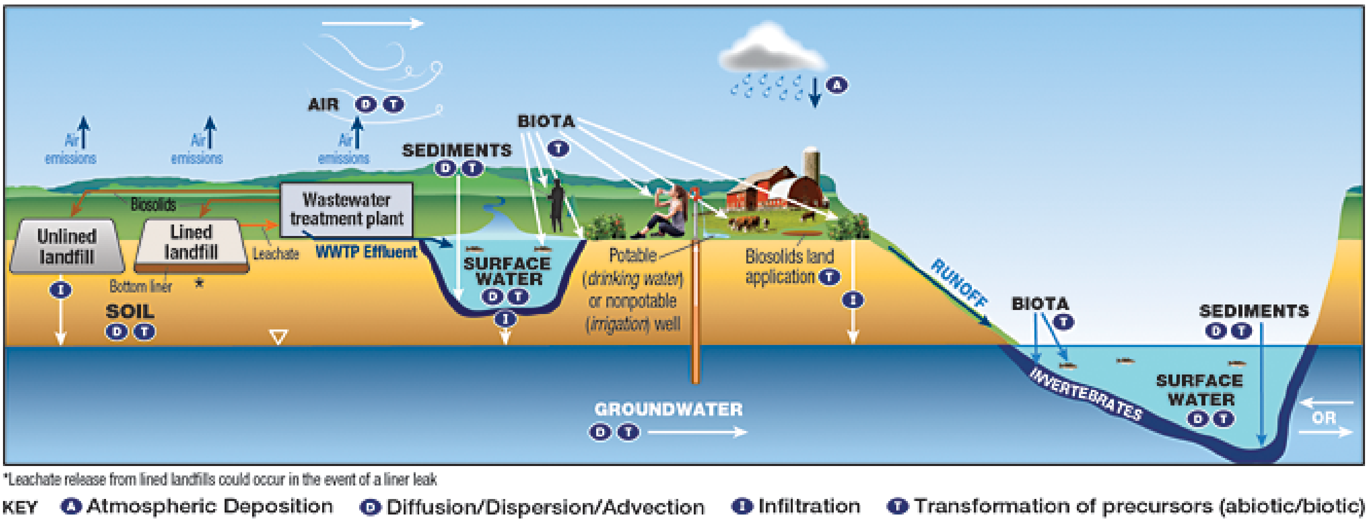


Figure 2-22. CSM for landfills and WWTPs.

Source: Adapted from figure by L. Trozzolo, TRC, used with permission.

2.6.3.1 Landfill Construction

Landfills are either lined or unlined (Figure 2-22). Municipal solid waste (MSW) landfills constructed since the 1990s are required by federal or state regulations to install a composite liner, a layer of compacted soil, and a leachate collection system (40 CFR 258.40). Although some states may have implemented construction standards at an earlier date, most landfills constructed before the 1990s were not required to have synthetic flexible membrane liners, compacted soil liners, or leachate collection systems, causing waste to be in direct contact with underlying soil or groundwater. Hazardous waste (Subtitle C) landfills have similar design requirements for the liner system, though an additional composite layer and leak detection layer are required (40 CFR 264.301). Construction and demolition (C&D) landfills or nonmunicipal solid waste landfills are subject to the requirements specified in 40 CFR 257 Part A (and if they intend to accept very small quantity generator waste, they are also subject to 40 CFR 257 Part B). Minimum design criteria for landfill liners are not specified in 40 CFR 257. Therefore, new C&D and nonmunicipal solid waste landfills may be permitted and constructed (or new cells added to existing facilities) without synthetic liners. Some states may have more restrictive requirements. Therefore, unlined landfills (and legacy disposal areas not classified as landfills) have a higher potential of contributing PFAS to groundwater (Oliaei et al. 2013). Properly constructed and operated modern landfills provide one of the few available disposal/management options for PFAS-containing waste, including wastewater solids, remedial/treatment waste, and consumer products. The USEPA Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances provides further discussion about the use of landfills for management of PFAS-containing wastes, the potential for PFAS to be released to the environment from landfills, and the additional research and data that are needed to further assess the effectiveness of managing PFAS discharges and emissions from all landfills (USEPA 2020).

Landfills are currently required to use a daily cover or alternate daily cover. It is acceptable for alternative daily cover to include materials such as sludge, sludge-derived products, shredded automotive parts, spray-on foams, and other materials (Pohland and Graven 1993) that are possible sources of PFAS. Landfill caps reduce infiltration of water to waste and may reduce the overall mass of PFAS entering the environment from a landfill, but more research on their effectiveness is needed (Hamid, Li, and Grace 2018).

Leachate from some MSW landfills has been shown to be a source of PFAS release to the environment (Busch et al. 2010; Eggen, Moeder, and Arukwe 2010), although the fate and transport processes for PFAS through landfills into leachate are not well understood at this time. The processes for managing leachate have implications on the ultimate fate and transport of PFAS. If landfill liners or leachate collection systems fail, PFAS may directly enter the environment. Leachate collected from landfills is typically treated on site or transported to either a WWTP or evaporation ponds. Modern landfills with properly constructed and operated liner and leachate collection systems should generally protect the underlying groundwater from PFAS releases. Leachate treatment by WWTPs is common prior to discharge to surface water or distribution for agricultural or commercial use (Lang 2016). However, standard WWTP technologies are generally ineffective at reducing or eliminating PFAS (Hamid and Li 2016; Ahrens et al. 2016; CRC CARE 2017). As a result, the discharge of landfill leachate, even if treated at WWTPs, can be a significant source of release of some PFAS to the environment (Ahrens et al. 2016; CRC Care 2017). Although landfill leachate PFAS concentrations can be relatively high, landfill leachate discharged to WWTPs for treatment generally is considered a relatively minor source to the environment because the volume of leachate generated annually and sent to a WWTP for treatment is low compared to the flow volume in most WWTPs (Busch et al. 2010; Masoner et al. 2020; MWRA 2019). On a site-specific basis, the impact of leachate on combined wastewater influent PFAS mass loading can vary depending on the relative volumetric contribution of leachate to combined influent flows and the nature of the landfilled waste materials (Masoner et al. 2020). Furthermore, USEPA's Effluent Guidelines Program Plan, (USEPA 2023) states "EPA evaluated discharge data from over 200 landfills from across the country and found PFAS present in the leachate at over 95 percent of the landfills. PFAS detections included 63 different PFAS with average concentrations for an individual compound as high as 14,000 parts-per-trillion (ppt)." However, in a limited study of five wastewater treatment facilities in Florida, Masoner et al. (2020) did not identify differences in the effluent PFAS loading of wastewater treatment facilities that received landfill leachate relative those that did not, suggesting the PFAS load present in wastewater treatment effluent is attributable to numerous sources. A similar finding was noted by MWRA (2019), though only PFOA and PFOS were investigated.

As part of EPA's final Effluent Limitations Guidelines Plan 15, USEPA (2023) announced its plans to proceed with a rulemaking to address PFAS discharges from landfills; refer to Section 16.6 for more information on this rulemaking.

2.6.3.2 Waste Age

Landfills containing sources of PFAS may continue to release PFAS to leachate at slow but relatively steady rates for decades following initial placement. In modeled anaerobic landfill reactors, most of the release is attributed to biological, not physical, mechanisms, indicating that the low solubility of the compounds is not solely responsible for slow release rates from landfills (Allred et al. 2015; Lang et al. 2016). Legacy industrial waste landfills may constitute a major source of PFAS release to the environment (ATSDR 2008, 2012).

2.6.3.3 PFAS Composition

PFAS composition and concentration in leachates vary depending on waste age, climate, and waste composition (Allred et al. 2015; Lang et al. 2017). Relative concentrations of PFAS in leachate and groundwater from landfills are different from those at WWTPs and AFFF-contaminated sites. PFAS with fewer than eight carbons tend to dominate landfill leachate because they are less hydrophobic and therefore more likely to partition to the aqueous phase (Huset et al. 2011; Higgins and Luthy 2007). In particular, 5:3 fluorotelomer carboxylic acid (FTCA) is a common and often dominant constituent of PFAS found in landfills and is released from carpet in model anaerobic landfill reactors. This compound could prove to be an indicator of PFAS in the environment originating from landfills (Lang et al. 2017, 2016).

PFAS may also be released to the air from landfills, predominantly as fluorotelomer alcohols (FTOHs) and perfluorobutanoate (PFBA). In one study, total PFAS concentrations were 5–30 times greater at landfills than at background reference sites (Ahrens et al. 2011). PFAS release rates vary with time for a given waste mass, with climate (for example, rainfall) as the apparent driving factor for the variations (Lang et al. 2017; Benskin et al. 2012). Gas collection systems commonly employed at modern landfills should reduce possible PFAS emissions to air.

2.6.4 Wastewater Treatment and Wastewater Treatment Residuals and Biosolids

Consumer and industrial use of PFAS-containing materials, including disposal of landfill leachate and firefighting foam, may discharge PFAS-containing wastewater to municipal and industrial WWTPs (Lin, Panchangam, and Lo 2009; Ahrens et al. 2009) private septic systems, or other wastewater disposal systems.

2.6.4.1 Wastewater Treatment

WWTPs receive PFAS from a host of sources conveyed thru and aggregated in effluent and sludges, which can provide the following pathways for PFAS releases to the environment (Figure 2-22):

- point source discharges of effluent
- leakage or unintended releases from surface impoundments and structures
- air emissions
- management (for example, land application) and disposal (for example, landfilling, incineration) of biosolids (https://www.epa.gov/biosolids), wastewater solids and sludges, and other byproducts generated during the treatment process (Section 2.6.4.2). Refer to Section 12 for more information on incineration.

The composition of PFAS in these media is a function of the different sources to the WWTP influent and the WWTP processes (Chen, Lo, and Lee 2012; Oliaei, Kessler, and D. Kriens 2006; Frömel et al. 2016; Schultz et al. 2006), including:

- type and concentration of PFAS received by the WWTP
- biological and chemical transformation of polyfluorinated substances (that is, precursor PFAS) to intermediate and terminal transformation products, such as PFAAs
- physical or chemical partitioning, or both.

In addition to PFAAs, fluorotelomer sulfonates, and sulfonamides, another family of PFAS precursor compounds, polyfluoroalkyl phosphate monoesters (PAPs) and polyfluoroalkyl phosphate diesters (diPAPs) (particularly 6:2 and 8:2 PAP; and 6:2 and 8:2 diPAP) have been documented in wastewater treatment plant (WWTP) samples and especially biosolids (Eriksson, Haglund, and Karrman 2016; Fredriksson et al. 2022; Kim Lazcano et al. 2020; Lee et al. 2014). This family of PFAS precursors plays an important role since they are typically found at much higher concentrations than commonly measured PFAS (Aro et al. 2021; Fredriksson et al. 2022; Moodie et al. 2021; Schaefer et al. 2022) and they have been shown to biotransform to PFAAs (Eriksson, Haglund, and Karrman 2016). Fredriksson et al. (2022) reported diPAPs accounting for 66% of the total concentrations of PFCAs precursors in sludge samples with the sum of diPAPs reaching up to 632 µg/kg, consistent with findings by Schaefer et al. (2022). As a result of precursor biotransformation, the concentrations of PFAAs can increase from influent to effluent, while the concentrations of these PFAS precursors decrease (Chen et al. 2018; Dauchy et al. 2017; Houtz, Wang, and Park 2018).

PFAS occurrence is reported in small municipal wastewater treatment plants with only domestic sources (Sinclair and Kannan 2006). PFAS in non-industrial wastewater is attributed to environmental transformation of polyfluorinated microfibers that might be released by different sources, for example, water-resistant clothing during laundry (Schellenberger et al. 2019), food packaging (Choi et al. 2019; Schaider et al. 2017), human excretion after oral exposure (Ma, Hongkai, and Kurunthachalam 2020; Worley et al. 2017), and tap water (Andrews and Naidenko 2020; Filipovic and Berger 2015).

Thompson et al. (2022) suggested that domestic wastewater accounts for most of the PFAS load in WWTPs while historically industrial discharges was believed to cause the majority of the PFAS releases from WWTP.

Conventional sewage treatment methods used in WWTPs do not efficiently remove PFAAs (Ahrens et al. 2011; Schultz et al. 2006). Even WWTPs with advanced treatment technologies (such as granular activated carbon (GAC), powdered activated carbon (PAC), or reverse osmosis (RO)) may not fully remove all PFAS if these systems were not designed with the intent to remove PFAS in addition to other targeted contaminants. Some PFAAs are frequently detected in WWTP effluent (for example, PFOA and PFBS), with concentrations of some PFAS up to hundreds of ng/L (Tavasoli et al. 2021). Ahrens et al. (2011) and Hamid and Li (2016) suggested that WWTP effluent can be a major source of PFAAs to surface waters.

Evaluation of full-scale WWTPs has indicated that conventional primary (sedimentation and clarification) and secondary (aerobic biotransformation of organic matter) treatment processes can change PFAS concentrations and subgroups. For example, studies have shown increased concentrations of PFAAs in effluent, presumably from transformation of precursor PFAS (Schultz et al. 2006), and the possible creation of PFAAs from the oxidation of polyfluorinated precursors during the treatment process (Oliaei, Kessler, and D. Kriens 2006; Frömel et al. 2016; Houtz, Wang, and Park 2018).

PFAS may be concentrated in wastewater solids (for example, sewage sludge) generated throughout the wastewater treatment process (Schultz et al. 2006). PFAS may also be present in septage (solids removed from septic systems). Depending on waste management and disposal practices, land application or landfill disposal of wastewater solids, biosolids, or septage could potentially contaminate the environment.

Hu et al. (2016) suggested that the presence of WWTPs in an area could be predictive of the presence of PFOS and PFOA in drinking water. PFOS and PFOA are two of the most frequently reported PFAS in wastewater (Hamid and Li 2016) in addition to other relevant PFAS such as diPAPs (Schaefer et al. 2023 and Thompson et al. 2023); see Section 6.2.3 for more information. Using WWTP effluent-impacted surface water as a source of drinking water can, in turn, recycle the PFAS back to the WWTP, recirculating PFAS in the water cycle (Hamid and Li 2016).

At some WWTPs, studies have shown concentrations of PFAS in ambient air at WWTPs to be 1.5–15 times greater than background reference sites (Hamid and Li 2016). Hamid and Li (2016) noted that these elevated air concentrations of total PFAS include polyfluoroalkyls and that this has important implications considering the potential for their long-range transport and subsequent transformation to recalcitrant PFAAs. PFAS distribution (primarily PFAAs and FTOH, with higher concentrations of FTOH) changes based on the specific PFAS sources in the effluent and the type of treatment methods employed at the WWTP.

Michigan EGLE has a program for evaluating PFAS in WWTP influent, effluent, and biosolids including conducting studies to better understand the fate and transport of PFAS from land application of biosolids (MI EGLE 2021). This included sampling of WWTP influent, effluent, and associated sludge or biosolids at 42 WWTPs and sampling of soils, groundwater, and surface waters at eight biosolids land application sites. The land application sites that received biosolids with “typical” levels of PFAS generally exhibited non-detectable to low concentrations of PFAS in soils, surface waters. The sites that received biosolids with higher PFAS levels that EGLE considered to be “industrially-impacted” showed higher concentrations of PFAS in the soils, surface water and groundwater with some results exceeding certain Michigan criteria. Results from the broad biosolids sampling were used to develop an Interim Biosolids Land Application PFAS Strategy (MI EGLE 2022), which in conjunction with the other State initiatives, allowed the majority of WWTPs to maintain the option to land apply biosolids while maintaining protectiveness. Restrictions were placed on land application of biosolids containing PFAS above certain criteria. Additional information about the MI EGLE biosolids programs are linked from their web site (https://www.michigan.gov/egle/about/organization/Water-Resources/biosolids/pfas-related).

Human exposure to PFAS can occur from wastewater through leaching into groundwater from biosolids land application or landfill operations, bioaccumulation into food or unplanned/planned potable reuse (Ahrens et al. 2011; Glover, Quinones, and Dickenson 2018; Hu et al. 2016; Lindstrom et al. 2011). More information about human exposures to PFAS is included in Section 9.1.2.

2.6.4.2 Biosolids Production and Application

Biosolids or “sewage sludge” are products of liquid separation from solids in wastewater treatment systems which undergo further physical chemical treatments to produce nutrient-rich products. Biosolids are residuals that have been treated thermally and/or chemically to meet state and federal standards to allow beneficial reuse. Biosolids are managed through beneficial reuse with land application (agriculture, turf grass, land reclamation) or composting (fertilizer) or disposed of by landfilling, incineration, or other form of surface disposal (NACWA 2023). Biosolids must meet state and federal requirements prior to land application in agricultural and reclamation sites. Land application of biosolids can offer economic and waste management benefits to municipalities and farmers (Stulp 1995). It should be noted that biosolids are not wastewater solids, industrial-derived sludges, or sludges that are the untreated solids/sludge removed during the process of treating wastewater.

PFAS are not known to be intentionally added to biosolids during processing or application since WWTPs are largely considered passive recipients of these chemicals.

PFAS presence in wastewater treatment residuals generated at municipal WWTPs is the result of widespread presence in engineered and natural systems, including numerous consumer products and certain industrial processes. The residuals can contain varying levels of PFAS commensurate with sewer shed characteristics, one of which is the type of and degree of influence that industrial dischargers have on municipal WWTPs. Several studies have reported results of testing of biosolids for PFAS (MI EGLE 2022). PFAS (measured as PFCAs and PFSAs) have been found in domestic sewage sludge (Higgins et al. 2005; Yoo et al. 2009), and PFAS occurrence in biosolids is reported to be prevalent and nationwide (Venkatesan and Halsden 2013).

There are a number of methods currently used to manage biosolids. According to USEPA (2023), around 43% of biosolids are land applied (typically as agricultural fertilizer), 42% landfilled, 14% incinerated, and 1% are stored or deep-well injected in the United States. The National Biosolids Data Project (https://www.biosolidsdata.org/) similarly reports about half of the biosolids are land applied, 25% are disposed in landfills, and 15% managed through incineration. Given the significant proportion of biosolids land applied for agriculture, there is the potential for release of PFAS to the environment associated with biosolids production and application. A small number of states have placed restrictions on incineration of PFAS containing material until the efficiency of destruction is better understood through on-going studies. Landfilling biosolids may lead to increased PFAS in landfill leachate which must be managed or increase the potential for releases to groundwater or air. However, there may be a greater reliance on landfilling in some states as restrictions are made on other management options. Long term landfilling of biosolids would also stress existing landfill capacity. In addition, a small number of states have also restricted the land application of biosolids due to concerns related to PFAS.

Biosolids can be land applied in several ways, including subsurface injection of liquid biosolids, surface application of liquid biosolids, surface application of dewatered (semi-solid) biosolids, or application and incorporation of dewatered (semi-solid) biosolids. Once introduced to the environment through land application, PFAS may enter surface water through runoff or infiltrate to groundwater (Lindstrom, Strynar, and Libelo 2011). Biosolids are also dried/pelletized for direct use as a soil amendment/fertilizer and for use in fertilizer blends that are then marketed commercially. The potential effects on groundwater or surface water may depend on many factors including but not limited to the amount and composition of PFAS present in biosolids, soil properties, infiltration rate, land application practices, land use, precipitation, climate, and land slope. PFAS concentrations can be elevated in surface and groundwater in the vicinity of agricultural fields that received PFAS-contaminated biosolids over an extended period of time (Washington et al. 2010). The Washington et al. study was completed in an area that received industrial wastewater discharges from several PFAS-related industrial dischargers. Other studies indicate that the potential PFAS releases from municipal biosolids (for example, those generated at WWTPs that do not receive significant inputs from industries linked to PFAS), may still impact water quality, but at an apparent lower relative impact than at the industrial-influenced biosolids application sites (Gottschall et al. 2017). Pepper et al. (2021) examined PFAS in soil in Arizona following long-term application of biosolids. The study concluded “long-term land application resulted in low incidence of soil PFAS” and “PFAS soil concentrations in irrigated agricultural plots with or without land application of biosolids were similar” (Pepper et al. 2021).

The most abundant PFAS found in biosolids (PFOS and PFOA) are the same as those found in WWTP effluent, although biosolids may also contain other long-chain PFAS (Hamid and Li 2016; Washington et al. 2010). Although multiple studies have reported statistically significant data showing transformation of polyfluorinated substances to PFAAs in land-applied biosolids (Yoo et al. 2010; Sepulvado et al. 2011; Washington et al. 2010), other evidence indicates that some polyfluorinated substances remain in biosolids-amended soils for many years to decades (Yoo et al. 2010; Rich et al. 2015; Washington et al. 2018).

Application of municipal or industrial biosolids as a soil amendment can result in a transfer of PFAS to soil (Sepulvado et al. 2011). These PFAS can then be available for uptake by some plants and soil organisms (Yoo et al. 2011). There are indications that PFAAs can enter the food chain through the use of biosolids-amended soil (Lindstrom, Strynar, and Libelo 2011; Blaine et al. 2013; Blaine et al. 2014; Navarro et al. 2017). It is noted, however, that PFAAs present at one municipal biosolids application site were not found in grain grown in the application plot (Gottschall et al. 2017). Hamid and Li (2016) suggested that short-chain (< C7) PFAAs in biosolids subsequently used in land applications can lead to contamination of food (Section 5.6). Significant data gaps exist regarding the fate and transport mechanisms associated with land application of PFAS impacted biosolids and the associated impacts to the food chain are an active area of study (see Section 6.5).

Refer to Section 2.7.4.1 for information on Michigan EGLE’s program for evaluating PFAS in WWTP influent, effluent, and biosolids including conducting studies to better understand the fate and transport of PFAS from land application of biosolids (MI EGLE 2021). The Environmental Council of the States (ECOS) collected information in November 2022 from state environmental agencies about management of biosolids and published a report of their findings (ECOS 2023).

Updated September 2023.

3 Firefighting Foams

The PFAS Team developed an Aqueous Film-Forming Foam training video with content related to this section.

The purpose of this section is to assist aqueous film-forming foam (AFFF) users (first responders, regulators, environmental managers, and environmental professionals) who manage AFFF releases. The section includes information about the applications, environmental impacts, and regulations associated with firefighting foams.

Section Number	Topic
3.1	Foam Formulations
3.2	AFFF Characteristics
3.3	Mechanisms for Release to the Environment
3.4	AFFF Fate and Transport
3.5	Forensic Analysis of AFFF
3.6	AFFF Procurement and Inventory
3.7	Foam Systems and Operations
3.8	Emergency Firefighting Operations
3.9	Immediate Investigative and Cleanup Actions
3.10	AFFF Disposal
3.11	Firefighting Foam System Replacement
3.12	Federal, State and International Regulations and Guidance
3.13	Foam Research and Development

It should be noted that the priority of firefighters and first responders is to protect life and property. The information provided supports decision-making about firefighting using AFFF so that potential impacts to the environment can be minimized and mitigated once the fire emergency is ended, or at such time that sufficient resources are deployed to the scene to both handle the fire emergency and mitigate the environmental risks posed by AFFF use. Fluorine-free foam (F3) alternatives are also discussed; these foams are not “film-forming” and are mechanistically different than AFFF in how they work to extinguish a fire. Figure 3-1 illustrates the life cycle considerations of AFFF. The considerations are discussed in subsequent sections.

Figure 3-1. Life cycle considerations for Class B Foams.

Source: S. Thomas, Battelle. Used with permission.

3.1 Foam Formulations

There are two major classes of firefighting foam, Class A and Class B foams. Class A foams are not considered in this document as they are intended for use on Class A or wood fuels. They are made from hydrocarbon-based surfactants, do not contain intentionally added PFAS, and are appropriate to use for their intended purpose. They are covered under NFPA 1150 (Standard on Foam Chemicals for Fires in Class A Fuels) (NFPA 2022).

Class B firefighting foams are commercial surfactant solutions that are designed and used to combat Class B flammable fuel fires. PFAS (fluorinated surfactants) are the active ingredient in Class B fluorinated foams. When mixed with water and discharged, the fluorinated foam forms an aqueous film that quickly cuts off the oxygen to the fire, cools it, extinguishes the fire, and prevents the fire from relighting. Class B foams have been (and continue to be) stored and used for fire suppression, fire training, and flammable vapor suppression at military installations and civilian facilities and airports (Hu et al. 2016), as well as at petroleum refineries and bulk storage facilities and chemical manufacturing plants (CONCAWE 2016). Additionally, local community fire departments have used and may maintain quantities of firefighting foam in their inventories for use in training and emergency response. Facilities that manufactured fluorinated firefighting foams and landfills that received firefighting waste are also potential sources of PFAS in the environment.

All Class B foams are not the same in composition and mechanism used to extinguish fire. Although not usually categorized this way from a fire protection viewpoint, they can be divided into two broad categories from a PFAS composition perspective: fluorinated foams that contain PFAS and F3 that do not contain PFAS. Figure 3-2 highlights the two broad categories of Class B foams and their subcategories.

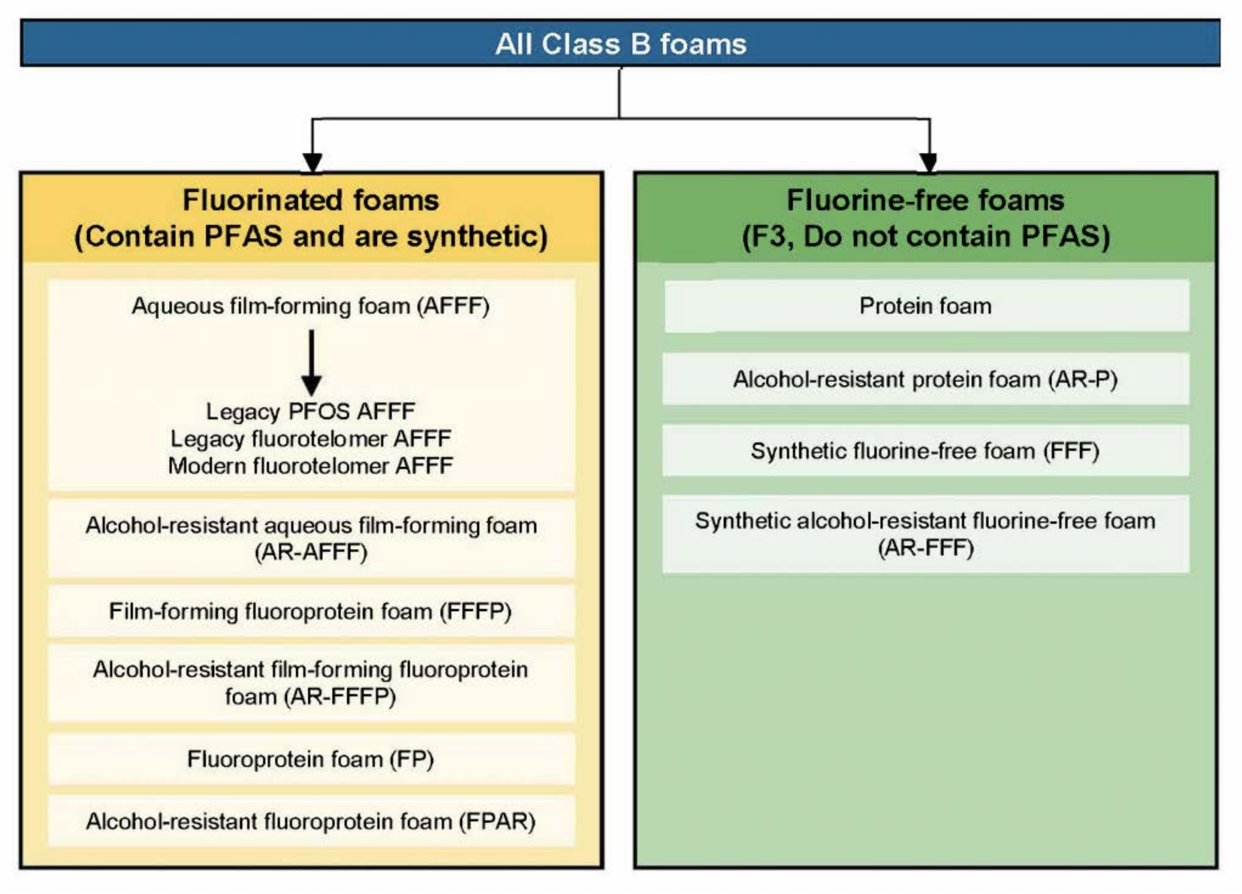


Figure 3-2. Types of Class B foams

Source: S. Thomas, Battelle. Used with permission.

All Class B foams have the potential to create an adverse environmental impact if released uncontrolled to the environment, particularly if the foam reaches drinking water sources, groundwater, surface water, or other natural waters. For all Class B foams, including F3, there is a potential for acute aquatic toxicity and excessive biological and chemical oxygen demand, as well as nutrient loading, depending on where the discharge occurs (see Section 3.11.1.3).

This section is focused on AFFF because of its long-term and widespread use and associated impacts to human health and the environment. AFFF is of particular concern because it contains PFAS.

As discussed elsewhere in this document, many PFAS are highly persistent and mobile in the environment and are not removed by traditional drinking water treatment methods typically used by public water suppliers.

Other foams such as alcohol-resistant foams (AR-AFFF), film-forming fluoroprotein foams (FFFP), alcohol-resistant film-forming fluoroprotein foams (AR-FFFP), fluoroprotein foam (FP), and alcohol-resistant fluoroprotein foam (FPAR), as illustrated in Figure 3-2, also contain PFAS and similar precautions and considerations should be taken.

The fluorosurfactants in AFFF formulations can be produced either using the electrochemical fluorination (ECF) process or the fluorotelomerization (FT) process. Both ECF-derived and telomer-derived AFFF contain diverse mixtures of PFAS (Barzen-Hanson et al. 2017). The ECF process results in a PFAS mixture dominated by perfluoroalkyl acids (PFAAs)—both perfluoroalkane sulfonate (PFSA) and perfluoroalkyl carboxylate (PFCA) homologues, while the fluorotelomerization process exclusively produces AFFF formulations consisting of polyfluorinated compounds (Houtz et al. 2013). ECF-based AFFF formulations were voluntarily phased out of production in the United States in approximately 2002 (Section 2.4.1). Despite the phaseout, however, ongoing permitted use of legacy AFFF can still result in long-chain PFAA contamination. Several organizations (for example, U.S. Department of Defense) commenced systematic replacement of legacy PFOS AFFF with modern fluorotelomer AFFF as early as 2018, but some legacy AFFF remains in service or stockpiled at other facilities (Section 3.11.1).

Fluorotelomer foams have been in use since the 1970s and became the predominant foam after 2001, when the major manufacturer (3M) of long-chain ECF-based foams (legacy PFOS foam) discontinued production (Leeson et al. 2021). Fluorotelomerization-derived AFFF is still manufactured and used in the United States but has been reformulated to limit, if not eliminate, long-chain PFAS; these foams are now referred to as modern fluorotelomer foams. Studies show ECF-based AFFF is a primary source of PFAS at AFFF-impacted sites, likely due to the longer period of ECF-based AFFF use and the relative coincidence of implementation of engineering controls for releases with increased use of telomer-based AFFF (CONCAWE 2016; Anderson et al. 2016).

To further classify AFFF products in terms of current usage and environmental considerations, they can be divided into three categories, including legacy PFOS AFFF, legacy fluorotelomer AFFF, and modern fluorotelomer AFFF (as shown in Figure 3-2).

- Legacy PFOS AFFFs were created in the 1960s by 3M and manufactured in the United States from the late 1960s until 2002 exclusively by 3M and sold under the brand name “Light Water” (USDOD 2014). 3M was the sole supplier from the mid-1960s until 1973. 3M did license some companies overseas to use their products and formulations. Legacy PFOS AFFFs contain PFOS and PFSAs such as perfluorohexane sulfonate (PFHxS) (Backe, Day, and Field 2013). Although phased out of production in 2002, legacy PFOS AFFFs are the dominant source of PFAS at AFFF-impacted sites (CONCAWE 2016). Furthermore, because of its long shelf life, stock of legacy PFOS AFFF could exist at any given fire department today.
- Legacy fluorotelomer AFFF were manufactured and sold in the United States from the 1970s until 2016 and encompass all other brands of AFFF besides 3M Light Water or their licensed products (Schultz et al. 2006). Specifically from 1973 onward, several manufacturers created fluorotelomer-based AFFFs that met the Mil-Spec criteria. Although they are not made with PFOA, they contain polyfluorinated precursors (Backe, Day, and Field 2013; Place and Field 2012) that are known to transform to PFCAs, including PFOA (Weiner et al. 2013; Harding-Marjanovic et al. 2015).

Modern fluorotelomer AFFF was developed in response to the USEPA 2010/2015 voluntary PFOA Stewardship Program (USEPA 2018). Most foam manufacturers have now transitioned to the production of only short-chain (C6) fluorotelomer-based fluorosurfactants. These modern fluorotelomer AFFFs, or “C6 foams,” do not contain or break down in the environment to PFOS or PFOA and are currently considered to be less toxic and have reduced bioaccumulative potential compared to long-chain (C8) fluorosurfactants. But under particular environmental conditions, breakdown products of C6 foams can include PFHxA, PFPeA, and 5:3 FTCA (Kempisty, Xing, and Racz 2018). Modern fluorotelomer AFFF may contain smaller levels of PFOA as an unintended manufacturing impurity or byproduct.

Fluorotelomer foams, short-chain fluorotelomer foams, and C6 foams are analogous and will be referred to as “modern fluorotelomer foams.” When discussing legacy PFOS or C8 foams, the term “legacy foams” will include both legacy PFOS AFFF and legacy fluorotelomer AFFF.

Legacy foams were first introduced by the naval firefighting services in 1964 (Gipe and Peterson 1972). The U.S. Naval Research Laboratory (NRL) began research on the development of firefighting foams in the 1960s. This led to advancements in fire suppression performance and increased firefighting safety (US Naval Research Laboratory 2017). In 1969, the U.S. Department of Defense (USDOD) issued military specification MIL-F-24385, which dictates the performance of all AFFF (with performance standards referred to as “Mil-Spec”). AFFFs shown to perform to MIL-F-24385 requirements are listed on the U.S. military’s AFFF Qualified Product Listing (QPL). The first date AFFF was placed on this list was May 15, 1970 (MIL-F-24385 QPL/QPD History of Type 6 AFFF). DOD maintains the online qualified products database (QPD) that lists all AFFF agents that have been tested and qualified by the NRL to meet the Mil-Spec, currently referenced as MIL-PRF-24385, (USDOD 2018). On July 1, 2006, the Federal Aviation Administration (FAA) required that commercial airports certified under 14 CFR Part 139 purchase only AFFF that is Mil-Spec compliant (FAA 2016; 14 CFR 139.317). The FAA Reauthorization Act modified that requirement. In January 2023, the performance specification for F3 land-based, freshwater applications was released as MIL-PRF-32725. This latest specification requires manufacturers to certify that PFAS has not been intentionally added to the formulation and that the concentrate contains a maximum of 1 ppb of PFAS (USDOD 2023). More information can be found in Section 3.12.3.

Different types of AFFF were produced to meet firefighting specifications, such as Mil-Spec, rather than formulated to contain a specified mixture of PFAS. AFFFs are a complex mixture of both known and unidentified PFAS. Multiple AFFF formulations have been produced over the years, and the exact composition of any given AFFF used or manufactured in any given year is variable (Backe, Day, and Field 2013). However, due to the production methods, any given AFFF formulation contains complex mixtures of PFAS, many of which can be identified only by nontargeted analytical methods (Barzen-Hanson et al. 2017) (see Section 11 for information about analytical methods).

AFFF is typically formed by combining hydrocarbon surfactants, organic solvents, fluorosurfactants, polymers, and other additives (Kempisty, Xing, and Racz 2018). AFFF concentrates are commercially available in 1%, 3%, and 6%. Figure 3-3 illustrates the typical composition of a 3% AFFF concentrate; estimates are that water/diluent makes up more than 60% of the concentrate, up to 20% is solvents, and as much as 15-18% is surfactants, of which less than 2% is fluorosurfactants. When the concentrate is mixed with water, the resulting solution achieves the interfacial tension characteristics needed to produce an aqueous film that spreads across the surface of a hydrocarbon fuel to extinguish the flame or reduce the hydrocarbon vapors. This is a general estimate and composition can vary.

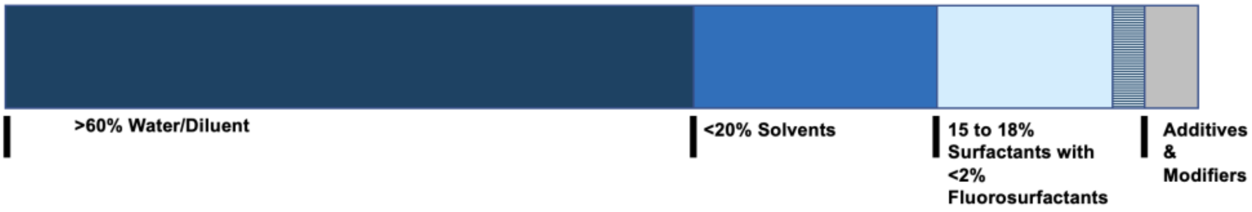


Figure 3-3. Typical composition of 3% AFFF concentrate.

Source: S. Thomas, Battelle. Adapted from Kempisty, Xing, and Racz 2018.

3.2 AFFF Characteristics

As sectors and industries continue to transition from fluorinated foams to F3s and investigation and remediation activities related to AFFF continue, an understanding of current and historical AFFF products is an invaluable asset to identify and delineate potential sources. This includes, where available:

- whether an AFFF product is/was considered a modern or legacy foam and if it is/was manufactured using fluorotelomerization or electrochemical fluorination
- when an AFFF product is/was approved for use and for what specific use/application and to what specific performance standard(s)
- any other pertinent and available information on the product (for example, compatibility, composition information, equipment requirements)

Table 3-1 provided as a separate Excel file, includes the above information for specific AFFF products.

Some research has been conducted to specifically characterize AFFF formulations in both legacy and modern foams. Barzen-Hanson et al. (2017) presented information about AFFF composition over time. Field et al. (2017) summarized information on the commercial formulations approved for use by the DOD in a document, “FAQs regarding PFAS associated with AFFF use at U.S. military sites.” Shojaei et al. (2022) characterized PFAS composition in Buckeye Platinum Plus C6 3% MS-AFFF (i.e., Platinum Plus C6) using targeted analysis, total oxidizable precursor assay (TOP), suspect screening, and nontargeted analysis. Results show that the sum of PFAS identified during target analysis comprised only 0.2 percent of total PFAS. 6:2 FTS and PFHxA were the most abundant target PFAS among the 12 monitored target PFAS. Suspect screening identified seven PFAS in six classes, which were largely comprised of C6 FT-based precursors (>99%). The most prevalent class was n:2 FTSAPr-DiMeAn, which may be a byproduct of fluorotelomer betaine synthesis. Nontarget analysis identified ten PFAS within nine classes of n:2 fluorotelomer sulfonamides, with 6:2 FTSAPr-AmHOPrS (CASRN 76201-56-4) being the most prevalent PFAS. PFAS composition of Platinum Plus C6 is different from the older Premium 3MS reported by Han et al. (2021).

ECF-based AFFFs contained primarily C6–C8 perfluoroalkyl sulfonates, with some zwitterionic C4–C6 perfluoroalkyl sulfonamides (FASAs) containing carboxylic acid and tertiary amine functionalities. Fluorotelomer-based AFFF formulations normally contained fluorotelomer thioamidosulfonates (FtTAoS) (4:2, 6:2 and 8:2) with 6:2 FtTAoS as the dominant compound, and very low perfluoroalkyl sulfonates or carboxylates (Backe, Day and Field 2013).

Some legacy nonfluorinated foams, notably those that are protein-based, form thick, viscous foam blankets on liquid hydrocarbon fuel surfaces. These foams are typically referred to as mechanical foams. These foams extinguish fires using strong bubble structure to smother the fire as opposed to the film and bubble structure of AFFF. More recent F3s are similar to the legacy protein foams in that they rely solely on the foam blanket to contain the fuel vapors to extinguish the fire (F3s do not produce a surfactant film on the fuel surface like AFFF). As a result, air-aspirating discharge devices may be required to optimize the capabilities of these products (NFPA Research Foundation 2022).

Many of the commercially available F3s have been tested to, and or listed/approved to, the legacy foam test protocols. These protocols include but are not limited to Underwriters Laboratories (UL), Factory Mutual (FM), European Standards (abbreviated EN), and International Civil Aviation Organization (ICAO) standards (NFPA Research Foundation 2022).

3.3 Mechanisms for Release to the Environment

Firefighting foam is applied by mixing foam concentrate and water to make the firefighting foam solution, which typically contains less than a fraction of a percent of fluorinated surfactants once in mixture. When applied to a fire, the foam solution is aerated at the nozzle, yielding finished firefighting foam. Thousands of gallons of foam solution may be applied during a given event. Figure 3-4 illustrates the use of firefighting foam, how it may be released to the environment, and potentially affected media. Once released to the environment, AFFF can contaminate soil, surface water, sediment, and groundwater. Section 5 includes details and references for fate and transport of PFAS in the environment.

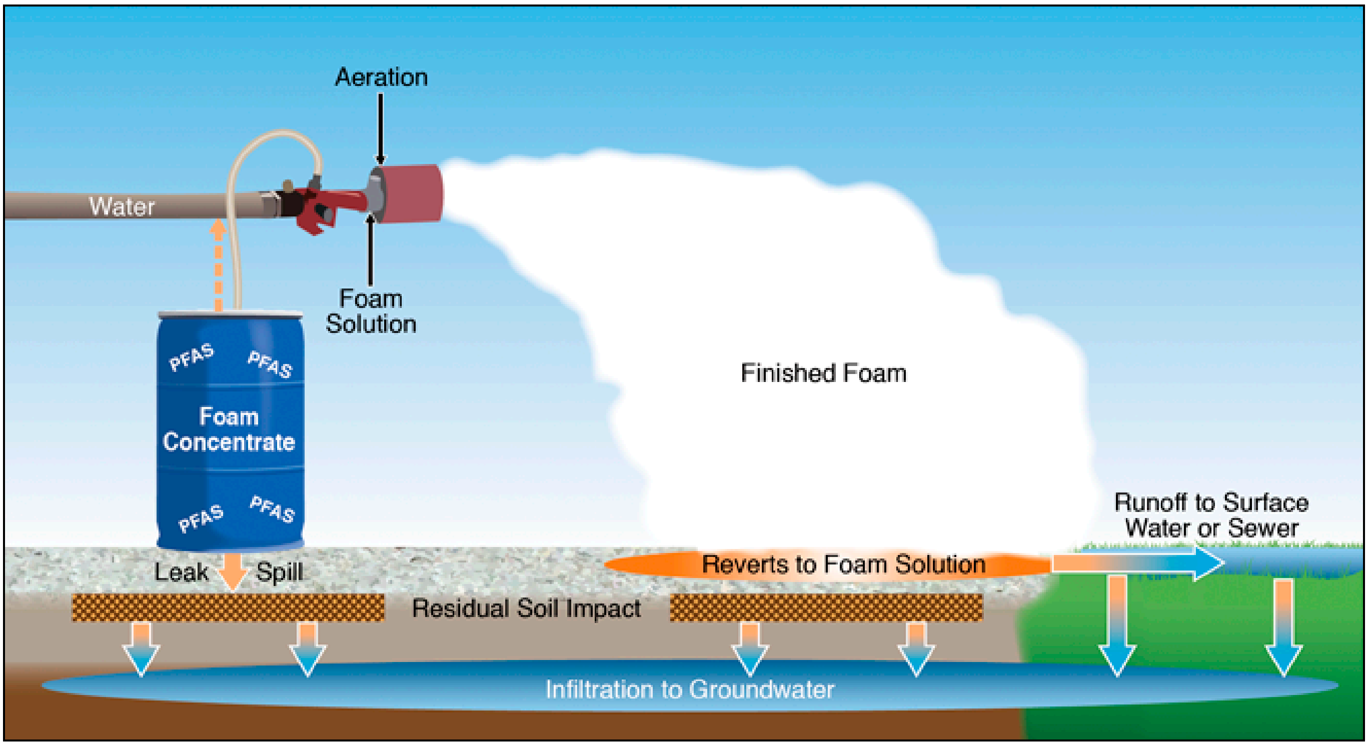


Figure 3-4. Release of firefighting foam.

Source: Adapted from figure by J. Hale, Kleinfelder. Used with permission.

Firefighting foams are released into the environment through various practices and mechanisms (Anderson et al. 2016; Hale 2016; Thalheimer et al. 2017) such as:

- low-volume releases of foam concentrate during storage, transfer, or operational requirements that mandate periodic equipment calibration
- moderate-volume discharge of foam solution for apparatus testing and episodic discharge of AFFF-containing fire suppression systems within large aircraft hangars and buildings

- occasional, high-volume, broadcast discharge of foam solution for firefighting and fire suppression/prevention for emergency response
- periodic, high-volume, broadcast discharge for fire training
- accidental leaks from foam distribution piping between storage and pumping locations, and from storage tanks and railcars.

AFFF-impacted sites often are also contaminated with petroleum hydrocarbons from unburned fuel. PFAS and hydrocarbon plumes at these sites may follow the same flow paths, though the extent of contamination may be significantly different. These co-contaminants, particularly light nonaqueous phase liquids (LNAPLs), may affect the fate and transport of AFFF-derived PFAS (Guelfo and Higgins 2013; Lipson, Raine, and Webb 2013; McKenzie et al. 2016), see Section 5.2.5. Certain air-based or in situ oxidation remedial activities aimed at treating co-contaminants may affect PFAS composition, fate, and transport as well (McKenzie et al. 2015). Additionally, the altered soil and groundwater geochemistry and redox conditions may result in oxidation of some PFAS precursor compounds, degrading them to terminal PFAAs (Harding-Marjanovic et al. 2016; McKenzie et al. 2016; McGuire et al. 2014). For additional detail on transformations of precursors see Section 5.4 and Section 10.4.6.

The USDOD has undertaken an evaluation of potential firefighting foam contamination at its facilities nationwide (Anderson et al. 2016). Similar efforts have been undertaken by some states. For example, the Minnesota Pollution Control Agency (MPCA) conducted a statewide survey of firefighting foam use at training sites. Working with the State Fire Chiefs Association, the MPCA identified more than two dozen locations where Class B foams were likely used in firefighting training (Antea Group 2011).

Figure 2-21 illustrates common elements of CSMs associated with the potential AFFF release scenarios at fire training areas.

3.4 AFFF Fate and Transport

3.4.1 Physical and Chemical Characteristics

Factors that affect fate and transport of PFAS from AFFF releases, as concentrate or in mixture with water, include the chain lengths of the PFAS, their ionic states, the type of functional group(s), and the extent of fluorination. These factors strongly influence the extent of PFAS partitioning and transformation that occurs in the environment. The distribution and composition of legacy PFOS AFFF and legacy and modern fluorotelomer AFFF differ in the environment based on their different chemical constituents and physical and chemical properties (MPART 2020). It is important to consider any precursor PFAS that can transform to PFAAs over time and add to concentrations of known PFAAs in the environment, such as PFOS and PFOA. The relatively high solubilities of most PFAS in AFFF contribute to their migration rates in groundwater. Current published data and physical properties of PFAS differ and some chemical data are experimental, extrapolated, or modeled. Section 4 summarizes some of the available physical and chemical properties for PFAS. Tabulated values and references are included in Table 4-1 (provided as a separate Excel file).

3.4.2 Fate and Transport Processes

Fate and transport process information is used to address questions related to potential risk, conceptual site model (CSM), and treatment of PFAS. The mechanisms of partitioning, transport, and transformation of PFAS, which occur across different environmental media, are summarized in Table 3-2 below. Section 5 provides the detailed discussion and references.

Table 3-2. Fate and transport process considerations

Fate and Transport Process	Description	Role in Transport
Partitioning Refer to Section 5.2	• Competition between hydrophobic and lipophobic C-F “tail” and nonfluorinated polar and hydrophilic head groups causes partitioning to interfaces such as: soil/water water/air water/NAPL co-contaminants	• Controls distribution in environment • Preference for air-water interface influences aerosol transport and deposition, and vadose zone transport (unsaturated conditions provide significant air water interfacial area)

Fate and Transport Process	**Description**	**Role in Transport**
Advection, Diffusion, Dispersion Refer to Sections 5.3, 10.4	• PFAS diffusion in groundwater is slow but greater in air and surface water • Atmospheric transport, e.g., from AFFF applications, results in deposition to soil/surface water/surfaces • PFAS are mobilized from soil to groundwater or to surface water through runoff and leaching	• Facilitate transport of PFAS in and across media • Increase contaminant distribution. Research on the potential impacts of diffusion on PFAS persistence in natural soils is ongoing. Adamson et al. (2020) conducted a study that estimated the relative distribution of different PFAS between high and low permeability soils at AFFF fire training area
Abiotic Transformation Refer to Section 5.4.4.1	• Abiotic processes that can transform precursors under ambient environmental conditions include hydrolysis, photolysis, and oxidation	• Results in chemicals with different physical and chemical properties • May alter risk • May affect treatment selection
Biotic Transformation Refer to Sections 5.4.4.2 and 5.4.4.3	• PFOA, PFOS, and other PFAAs are resistant to microbial degradation • Biotransformation of various precursors has been reported	• Results in chemicals with different physical and chemical properties • May alter risk • May affect treatment selection

3.4.3 Fate and Transport Considerations for AFFF Remediation

Knowledge of the type of AFFF and the constituents released to the environment is critical for adequate site characterization and CSM development. Physical and chemical properties and environmental processes play key roles in identifying contaminant capture and collection methods and selection of treatment technologies. The effects of co-contaminants, such as petroleum hydrocarbons, on fate and transport of AFFF constituents is addressed in Section 3.3 and partitioning into NAPL co-contaminants is addressed in Section 5.2.5. Many traditional technologies, such as air stripping and soil vacuum extraction, which rely on volatilization, have been found to be ineffective for PFAS, which typically have low volatilities and are highly soluble. The stability and persistent nature of PFAS in the environment also make current bioremediation approaches ineffective.

Proven and developing treatment technologies for treatment of PFAS are presented in Section 12, which also includes details on the roles of physical and chemical characteristics and transport processes in technology selection. For example, water treatment technologies, such as GAC adsorption and ion exchange, have been proven to be effective because they rely on the hydrophobic and ionic properties of PFAS. Field-implemented technologies for soil include excavation and landfill disposal or mixing with sorbent for stabilization. The potential for leaching associated with disposal is reduced by stabilization. Many new technologies that rely on the unique properties of PFAS are under development.

3.5 Forensic Analysis of AFFF

Forensic analysis of AFFFs should be based on fingerprinting the composition of unknown samples and comparison with published fingerprints that are further discussed in this section. Many limitations must be considered in such investigations, including the changes in original manufactured product fingerprint due to precursor transformation in time, potential presence of impurities due to manufacturing processes and/or equipment used, and differences in original fingerprints for distinct manufactured batches. While there are tests that may be performed to help understand and overcome some of these limitations, every case should be based on site-specific data and historical information. For example, total oxidizable precursors (TOP) may be performed to evaluate the changes in original AFFF fingerprints due to precursor transformations in time and the data should be interpreted within site-specific context considering potential deviations due to site-specific conditions. AFFF products stored for long periods of time may have changed the original PFAS fingerprint even if those products were not released and exposed to environmental conditions. Therefore, when trying to identify the type and original composition of AFFF products, multiple lines of evidence should be employed, including historical information, chemical fingerprinting via targeted PFAS analysis, TOP analysis, and total organic fluoride (TOF) content. Ultimately, nontargeted PFAS analysis may also be employed for in-depth evaluations and matching of foams with suspected sources. More information on these specific tests is provided in Section 10.5 and Section 11.

Although many types of PFAS are identified in the AFFF formulations, due to the lack of analytical standards, quantitative information is not available for all identified individual PFAS, whereas qualitative detections and area counts are reported (D’Agostino and Mabury 2014; Barzen-Hanson et al. 2017; D’Agostino and Mabury 2017; Ruyle et al. 2021). There is quantitative information on the composition of a series of AFFF formulations manufactured in different years by several manufacturers, including 3M, ChemGuard, Ansul, Buckeye, and National Foam (Annunziato et al. 2020; Houtz et al. 2013; Backe, Day, and Field 2013; Ruyle et al. 2021; Herzke, Posner, and Olsson 2009; KEMI, 2015). The chemistry of AFFF is complex, consisting of anionic, cationic, zwitterionic, and neutral compounds; in addition, different formulations of AFFF from the same manufacturer may also vary in chemistries (Backe, Day, and Field 2013; Houtz et al. 2013; Barzen-Hanson et al. 2017). AFFF includes many fluorinated and nonfluorinated surfactants. Total surfactants are thought to range from approximately 15 to 18 percent. Some references cite about 5–10% (w/w) are nonfluorinated surfactants and 0.9–1.5% (w/w) are PFAS (Backe, Day, and Field 2013; D’Agostino and Mabury 2014). These nonfluorinated surfactants have also been detected in the AFFF-impacted groundwater (García et al. 2019). For forensic analysis, evaluating the source attribution of PFAS from AFFF used for emergency response or fire training operations and understanding the manufacturing history, timing of release, potential sources, degradation products, isomer profiles, and environmental partitioning of PFAS during transport are very important (Dasu et al. 2022; Guelfo et al. 2021; Dorrance et al. 2017).

3.5.1 Manufacturing and Chemistry

PFAS are commonly produced by two manufacturing processes: electrochemical fluorination (ECF) and fluorotelomerization. For example, legacy 3M AFFF brand name Light Water was manufactured by electrochemical fluorination, and the legacy longer chain and the new replacement shorter chain (C6) fluorotelomer-based AFFFs are manufactured by the fluorotelomerization process. More detailed information on these processes is presented in Section 2.2.5, and more detailed information on AFFF as it relates to these processes is presented in Section 3.1. Despite the recorded differences and complex composition of AFFF products, several general traits have been established in the literature based for each manufacturing processes and the final products and byproducts formed by using these two processes are different.

The ECF process results in a mixture of linear and branched fluorinated molecules of various carbon chain lengths, both even and odd carbon chains (Buck et al. 2011). The ratio of linear and branched isomers ranges from 70 to 80% linear and 20 to 30% branched isomers (Kissa 2001; Buck et al. 2011; Benskin et al. 2007). The ECF process produces varying amounts of C2–C10 PFAAs (Backe, Day, and Field 2013). Some of the ECF chemistries are based on perfluorooctane sulfonyl fluoride (POSF), a major raw material used to manufacture surfactants (such as perfluorooctane sulfonate (PFOS)), and other raw materials such as sulfonamides, sulfonamido alcohols, and related monomers (Backe, Day, and Field 2013; D’Agostino and Mabury 2014; Buck et al. 2011).

The other important manufacturing process of PFAS is the telomerization process, which mainly produces linear isomers with an even number of carbon chains as the major products, although some odd-numbered carbon chains have also been produced (Kissa 2001). The nomenclature of PFAS manufactured by the telomerization process includes n:2 fluorotelomers (see Section 2.2.4.1), where n represents the perfluorinated carbon chain length and 2 represents the nonfluorinated ethane attached to the functional group, such as alcohols, carboxylates, sulfonates, etc. (Buck et al. 2011). Fluorotelomers (FT) are predominantly produced in 4:2-, 6:2-, 8:2-, and 10:2-carbon chain lengths, although 12:2 has been seen in FT Mil-Spec AFFF (Backe, Day, and Field 2013). Fluorotelomer alcohols or iodides are commonly used as raw materials in the telomerization process to produce fluorotelomer sidechain polymers. At many of the AFFF-impacted sites, perfluorooctanoic acid (PFOA), PFOS, and perfluorohexane sulfonic acid (PFHxS) are the most prevalent PFAS detected. The phaseout of the longer chain PFAS by global manufacturers has resulted in quantifiable increase in shorter-chain concentrations and decreased concentrations of longer chains at some of the areas investigated (Ruyle et al. 2021).

3.5.1.1 Reported PFAS Profiles in AFFFs Manufactured Via ECF vs. Telomerization.

In spite of the recorded differences and complex composition of AFFFs, several main traits may be established among AFFFs manufactured by each mentioned process based on the literature-reported data (Annunziato et al. 2020; Houtz et al. 2013; Backe, Day, and Field 2013; Ruyle et al. 2021; Herzke, Posner, and Olsson 2009; KEMI 2015). These traits provide the basis for chemical fingerprinting of PFAS in AFFFs and environmental media.

AFFFs manufactured via ECF process (by 3M) are reported to contain both precursor PFAS (including: PFBSAm, PFPeS-Am, PFBS-AmA, PFPeS-AmA, and PFHxS-AmA) and PFSAs (which are typically predominant) and PFCAs. The AFFFs manufactured via fluorotelomerization process are reported to contain mostly precursor PFAS, with some PFCAs also being reported in some of these AFFFs (Ruyle et al. 2021). Upon oxidation (for example, transformation of precursor PFAS in time and due to exposure to environmental conditions), both main types of AFFFs generate PFCAs with distinct profiles described below.

- The profiles of PFCAs in ECF-manufactured AFFFs after oxidation are consistent among various manufactured batches and years and are different from the profiles reported before oxidation. The oxidized ECF-manufactured AFFFs PFCA profiles should be more representative for environmental profiles of spilled AFFFs and have the following common traits: the predominance of PFHxA (61–75%), followed by PFBA (12–26%), and PFPeA (2–25%) (Houtz et al. 2013). Smaller amounts of PFOA and PFHpA are also reported in these oxidized foams.
- The profiles of PFCAs in AFFFs manufactured by telomerization generated after AFFF oxidation have several common traits among manufacturers (for example, Chemguard, Ansul, Buckeye, National Foam), which seem to be preserved along the years. These traits include the predominance of PFPeA (25–49%), followed by PFBA (19–28%), PFHxA (13–20%), and PFHpA (3–20%), and the presence of smaller amounts of PFOA (1–9%) and PFNA (1–4%) (Houtz et al. 2013).
- The profiles of PFSAs in manufactured (nonoxidized) AFFFs are preserved among ECF-manufactured AFFFs from different years (1988, 1989, 1992, 1993, 1998, 1999, 2001), including batches from the same years, as reported by Houtz et al. (2013). The PFAS profiles of 3M-manufactured AFFFs are consistent in the strong predominance of PFOS (85–90%), followed by PFHxS (7–12%), with smaller amounts of PFHpS and PFBS also detected. Similar profiles are reported by Backe, Day, and Field (2013) and by Ruyle et al. (2021), with the addition of PFPeS detected in small amounts.
- The profiles of PFCAs in manufactured AFFFs (non-oxidized) vary more among the reported manufactured batches and years than in the case of the PFAS profiles mentioned before. Despite these variations, several traits can be observed: In some of the analyzed AFFFs manufactured by ECF (Houtz et al. 2013), PFPeA predominates, followed by PFHxA and PFOA, while in ECF-manufactured AFFFs analyzed by other authors, these proportions change to some extent with the predominance of PFHxA and PFOA, and with smaller amounts of PFPeA, PFBA, and PFHpA also reported (for example, see data reported by Backe, Day, and Field 2013, Annunziato et al. 2020, and Ruyle et al. 2021).

In AFFFs manufactured by telomerization, only a few had PFCAs detected before oxidation and the profiles were quite variable, as reported by Ruyle et al. (2021), with the predominance of PFHxA and PFBA in many analyzed foams, and the predominance of PFHpA, PFOA, and PFNA in few other foams. In several different analyzed foams, Herzke, Posner, and Olsson 2009 reported the predominance of PFHxA and PFPeA, followed by PFOA and PFBA, with PFDcA (at comparable amounts with PFBA) reported in one foam, while smaller amounts of PFDoA were reported in another foam.

Benotti et al. (2020) reported PFAS profiles for several FT-manufactured modern AFFFs, consistent with those described here and reported by other authors mentioned before (for example, Herzke, Posner, and Olsson 2009), consisting predominantly of 6:2 FTS among detected precursor PFAS and PFHxA among detected PFCAs. Additionally, the Benotti et al. (2020) study pointed out the predominance of even-numbered PFCAs (PFBA, PFHxA) over their odd-numbered homologues in AFFFs manufactured via telomerization. Notably, this study also pointed out the presence of smaller amounts of long-chain PFCAs (including PFOA, PFDA, PFDoA) and PFSAs (PFHxS and PFOS) in the modern AFFFs that were analyzed. The authors attributed these findings to the manufacturing process from fractional distillation of feedstock or to cross-contamination during manufacturing and handling.

3.5.2 Factors Affecting the PFAS Fate and Fractionation

PFAS forensic analysis of environmental samples is often challenging as many of the PFAS-contaminated sites consist of comingled sources. Many of the AFFF-impacted sites often contain a mix of different formulations of AFFF, either from the same manufacturing source (ECF or telomer-based), or a mix of different sources. Many of the PFAS analytes exhibit a wide range of physical and chemical properties, and hence are transported from the source zones and redistributed downstream through environmental fractionation (Lindstrom et al. 2011; McGuire et al. 2014). Higher water solubility and mobility of short-chain PFAS contribute to the relatively high concentrations of short-chain PFAAs in aqueous matrices downstream from the source areas. The isomer profiles present at the source of contamination will change and redistribute after a certain distance from the source (Adamson et al. 2020; Nickerson et al. 2021). Due to the high solid/water distribution coefficient (K_d), longer chain PFAS have a greater affinity than shorter chain PFAS to partition to sediments, sludge, and soils (Higgins and Luthy 2006; Kwadijk, Korytár, and Koelmans 2010; Schulz, Silva, and Klaper 2020). PFAS, due to their electrostatic nature, may also adsorb onto soils due to the soils' electrostatically charged surfaces (Adamson et al. 2020). Groundwater transport of PFAAs depends on the concentration, chain length, soil characteristics, partitioning behavior, and in situ precursor biotransformation followed by the redistribution of the transformation products (Guelfo and Higgins 2013; McGuire et al. 2014; Anderson et al. 2016). Additionally, the presence of co-contaminants and/or remediation products in subsurface may also affect PFAS fate and transport (Guelfo and Higgins 2013; McKenzie et al. 2015; Brusseau 2018; Hatton et al. 2018) and should be considered in a forensic investigation.

All these factors indicate that the PFAS fingerprint at the source could be different compared to the downstream sample locations. Hence, forensic analysis of such complex AFFF-impacted comingled sources would require consideration of many factors and multiple lines of evidence to better understand the identification and delineation of sources. These include: (1) PFAS profiles, including PFCAs and PFSAs isomer profiles and chain-length ratios, which may differ from source, based on the environmental fractionation; (2) unique source-specific markers, which require a detailed understanding of known sources to identify a source related to a sample (McGuire et al. 2014; KEMI 2015; Guelfo and Adamson 2018); and (3) high-resolution mass spectrometry (HRMS) tools to help identify and characterize a broad suite of PFAS analytes to understand the source-specific markers (D'Agostino and Mabury 2014; Barzen-Hanson et al. 2017; D'Agostino and Mabury 2017; Newton et al. 2017; Ruyle et al. 2021). In addition to HRMS analysis, application of statistical analysis tools showed great promise in identifying sources of PFAS contamination (Zhang et al. 2016; Kibbey, Jabrzemski, and O'Carroll 2020; Nason et al. 2021). However, statistical analysis of any PFAS data sets should be done with caution, considering comparability between data sets in terms of sampling and analytical techniques used, as well as environmental transformations expected based on sample location and site-specific parameters. A forensic approach based on multiple independent lines of evidence increases certainty. Examples of lines of evidence that may be developed for PFAS forensic evaluation include chemical profiles of PFCAs and PFSAs, isomer profiles, signature PFAS (for example, via nontargeted analysis), historical document review, and fate and transport evaluation and modeling (see also Sections 4, 5, 10, and 11).

3.5.3 Summary of Forensic Analysis of AFFF

Employing a lines of evidence approach to identify what AFFF product or products have been used at a particular site is a useful first step during site assessment. The identification of products may help the practitioner to predict what PFAS compounds may be present, including likely precursors and degradation products. Understanding product use will improve site conceptual model development at the outset. Lines of evidence that may be used to identify AFFF products include interviews with site users, bills of lading or procurement records, and finally, analysis of environmental samples. Foam product groups (for example, legacy ECF-manufactured AFFFs, legacy fluorotelomer AFFFs, and modern AFFFs) differ in key ways as presented below.

The proprietary nature of source information, complex PFAS chemistry, and lack of analytical standards pose many challenges in understanding the source identification (see also Section 10.5 and Section 11.4) and attribution at AFFF-impacted sites. Using only targeted PFAS analysis may be useful, since several common traits are evident in AFFFs and may help differentiate between AFFFs and other types of PFAS sources. However, differentiation between multiple AFFF sources may become more difficult based just on targeted analysis data (for example, PFCA and PFSA data), especially for comingled plumes away from the source area where environmental fractionation may play an important role. Nontargeted analysis using HRMS helps in understanding the chemistry beyond the standard targeted analysis data and shows great promise in identifying and delineating PFAS contamination; however, HRMS is still a relatively new and developing tool and its results should be interpreted carefully in the context of the specific investigation. Considering multiple lines of evidence while conducting forensic investigations helps to identify PFAS source attribution and manage AFFF-impacted sites.

A series of recent publications provide data and information relevant to AFFF source evaluation, as synthesized below:

- AFFF fingerprints seem to be preserved in fish from polluted freshwater systems and were used to differentiate AFFF versus other PFAS sources in fish, namely the paper industry and long-range atmospheric transport (Langberg et al. 2022). Specifically, a total of 454 liver samples and 581 muscle samples from 11 fish species were investigated. The fish samples from AFFF-polluted sites had a predominance of PFOS, suggestive of legacy ECF-manufactured AFFFs. High percentages of PFOS were also observed in fish samples contaminated from the paper industry, but the PFCA profiles were distinct from those in fish contaminated by AFFFs. In fact, the profiles of PFCAs were distinct between AFFFs and the other PFAS sources (paper industry and long-range atmospheric transport). The PFCAs profiles in fish from waters contaminated from the paper industry and via long-range atmospheric transport had higher percentages of long-chain PFCAs, as compared with those from fish in waters contaminated by AFFFs. Additionally, PFUnDA/PFDA and PFTrDA/PFDoDA ratios were different between the two non-AFFF sources, being higher in the case of long-term atmospheric transport.

- Dasu et al. (2022) performed a comprehensive review of PFAS concentration profiles from both main direct (fluorochemical manufacturing plants, consumer products, metal-plating operations, AFFF use) and indirect sources (landfills and wastewater treatment plants). They found that both groundwater and soil at or near AFFF-contaminated sites had higher median PFOA and PFOS concentrations as compared to those from groundwater and soils near the other main studied sources. Dasu et al. (2022) pointed out the potential for environmental transformation of many unknown PFAS present in AFFF into persistent PFAS, acting as long-term PFAS sources. From a fingerprinting perspective, the study indicates that the commonly analyzed PFAS compounds are ubiquitously detected in environments contaminated by distinct main sources, pointing out the need for high-resolution tools such as nontargeted analysis and combined methods of total fluorine and/or extractable fluorine for better source attribution of PFAS. However, Dasu et al. (2022) did not include an analysis of the relative proportions of individual PFAS compounds in media contaminated by different sources, which could have forensic relevance.
- The high precision methods used by Liu et al. (2022) in analyzing PFAS-contaminated soil and groundwater at four Canadian airports, consisting of HRMS and an improved total oxidizable precursor (TOP) assay, may be of high utility in forensic applications. Based on these analytical techniques, 93 classes of PFAS could be investigated and characterized at these Canadian airports.
- A comprehensive study of PFAS in surface water near U.S. Air Force bases (East, Anderson, and Salice 2021) determined that, according to the legacy AFFF composition, a four-chemical mixture composed of PFOS, PFHxS, PFHxA, and PFOA generally accounted for >80% of the sum of all routinely reported PFAS in a sample. This observation is relevant in building AFFF-representative PFAS fingerprints.
- The predominance (90%) of 6:2 fluorotelomer sulfonate in modern AFFFs has been confirmed by Ruyle et al. (2021), who developed and applied a "novel method (Bayesian inference) for reconstructing the fluorinated chain lengths, manufacturing origin, and concentrations of oxidizable precursors obtained from the total oxidizable precursor (TOP) assay" (Ruyle et al. 2021). These authors were able to identify 14 major fluorotelomer compounds present in modern AFFF "yielding a priority list that accounts for almost all detectable PFAS in contemporary AFFF." Testing for these fluorotelomers may help differentiate between AFFF and non-AFFF sources of PFAS.
- Kibbey, Jabrzemski, and O'Carroll (2020) "explored the use of supervised machine learning classifiers for allocating the source of PFAS contamination based on patterns identified in component concentrations." "The deep neural network and Extra Trees exhibited particularly high performance at classification of samples from a range of sources, [showing that] patterns exist in PFAS water sample data that can allow forensic source allocation." While these methods are complex and evolving, they show promise for PFAS allocation at complex sites.
- Shojaei et al. (2022) provided useful data on the chemical composition of AFFFs currently certified for use by the U.S. military. These authors used several distinct analysis techniques, including targeted analysis by HRMS, TOP, and nontargeted analysis. The study identified nine novel classes of PFAS comprising 10 individual compounds that made up ~90% of total PFAS measured in the tested foam. The combination of TOP with nontargeted analysis holds great potential for PFAS source identification.

3.6 AFFF Procurement and Inventory

This section discusses procurement and inventory of AFFF, including suggestions for storing inventory to minimize the potential for accidental releases.

3.6.1 Foam Selection and Requirements

Multiple manufacturers in the United States and abroad produce AFFF concentrate in 1%, 3%, or 6% concentrations. Most AFFF sold or in stock in the United States is either 1) listed by Underwriters Laboratory (UL) based on conformance with UL

Standard 162, “Foam Equipment and Liquid Concentrates,” or 2) tested by NRL and granted qualification by U.S. Naval Sea Systems Command in accordance with the Mil-Spec. Only AFFF meeting the Mil-Spec has been used in military applications and at FAA-regulated airports.

Military and FAA AFFF applications subject to Mil-Spec account for more than 75% of AFFF used in the United States (Airport Cooperative Research Program ACRP (2017)). Hence, the production of AFFFs has historically been driven by firefighting specifications, such as Mil-Spec, which requires a specific percentage concentration of PFAS. Current Mil-Spec AFFFs contain ≤ 1% (approx. 0.5–0.6%) fluorosurfactants after the concentrate is mixed with water to create the final foam solution used to extinguish or prevent high-hazard flammable liquid fires; however, the exact AFFF PFAS mixtures are highly variable. Non-Mil-Spec Class B foams can vary from fluorine-free to having concentrations of PFAS similar to Mil-Spec AFFF. Furthermore, where fire risk allows it, users who are not subject to Mil-Spec requirements are less likely to use foam formulations that contain PFAS given the environmental implications and increasing prevalence of F3. However, the knowledge of environmental implications of PFAS was historically lacking and is still not widely understood by first responders, and there are many historical examples of AFFF use by municipal fire departments during fire response activities.

3.6.2 AFFF Storage and Handling

AFFF concentrate is available from the manufacturers in containers ranging from 5-gallon buckets to 5,000-gallon tanker trucks. The most common method of shipping is in 5-gallon buckets, 55-gallon drums, or 265-gallon intermediate bulk containers. Shipping containers are typically not double walled but made of plastic, steel, or steel reinforced plastic tote construction to resist damage/puncture. Per National Fire Protection Association (NFPA) 11, Section 4.3.2.3, bulk liquid storage tanks should be fabricated from or be lined with materials compatible with the concentrate, designed to minimize evaporation of foam concentrate, and stored within the listed temperature limitations (NFPA 2016).

In fire suppression systems, the AFFF concentrate is typically stored in either an atmospheric (nonpressurized) tank or a bladder tank (pressurized). Atmospheric tanks are single- or double- walled tanks and can supply proportioning foam concentrate pumps or venturi-based proportioners that feed the suppression system. Atmospheric tank piping arrangements may include recirculation from downstream of the pump back to the tank. The bladder tanks contain a bladder filled with foam concentrate that is squeezed by water between the shell of the tank and the bladder. As long as the bladder integrity is maintained, the foam concentrate does not mix with the shell water.

Safety data sheets are provided by all manufacturers for each specific type of AFFF. Labels on shipping containers conform to U.S. Department of Transportation (USDOT) standards. AFFF and AFFF-impacted materials (soils and absorption materials), including concentrate being disposed, rinsate, and foam supply system materials, are not currently considered to be hazardous materials under federal regulations. Some individual states have passed legislation to include PFOS, PFOA, and other PFAS on their hazardous substances list and otherwise restrict the sale and use of AFFF (for example, (Washington Senate 2018) (New York State 2017). Regulations are discussed further in Section 3.12

As with any potentially hazardous substance, the best practice for storage and handling is to ensure containment until proper disposal. AFFF materials should be labeled to clearly indicate the contents of the container. It is important that all containers are kept clean so that any signs of leakage can be easily and quickly identified during container inspections, with the labeling pointed outward for easier reading.

3.7 Foam Systems and Operations

Class B firefighting foams are employed globally to fight flammable liquids fires where risk of damage to property or human life is high. These products are particularly prevalent in airport settings. This section describes common AFFF system operations, including system testing and training. Additionally, information is provided in Section 3.11 for organizations that want to replace legacy PFOS AFFF systems with modern fluorotelomer AFFF or F3.

3.7.1 Fixed System Testing

Fixed fire suppression systems that utilize any of the foam types and application methods are permanent designs and should incorporate the containment, collection, and runoff components in the event of system discharge into the design. Examples include flammable liquid warehouse, waste treatment facility, and aircraft hangar fire suppression systems. New systems should be designed to include foam containment and collection mechanisms such that foam releases that occur during testing or activation are not released to the environment, or the AFFF can be captured for disposal. AFFF design standards require minimum durations for foam system discharge to meet the suppression/control requirements and in some cases require specific volumes of concentrates and foam solution to be contained in on-site storage tanks. Fixed AFFF proportioning systems that are connected to city water mains should be fitted with backflow preventers to protect the city water mains from potential AFFF contamination.

Codes, standards, and authorities having jurisdiction over fixed system testing, such as NFPA Standards 16 (NFPA 2019) and 25 (NFPA 2017), can require that the equipment produce a foam/foam solution that can be tested and compared to laboratory standards. System testing generates a small amount of foam that should be contained or controlled by the design to the best extent possible for proper disposal. Foam can be wetted with fog nozzles/mist to knock down the foam and dilute it. Gentle squeegee and sweeping are required to keep the solution from aspirating during cleanup and dilution. Alternatives, such as testing with water (without foam) or testing with fluorine-free training foam or surrogate liquids having similar physical properties, may be considered to minimize disposal issues. Check applicable regulatory requirements for testing to determine frequency and type of testing required, as well as what is specifically mandated for foam type before any alternatives are considered to ensure compliance with appropriate laws.

3.7.2 Mobile Firefighting Equipment Testing

Firefighting equipment requires inspection, calibration, and testing to ensure reliability and performance to specifications. In accordance with fire protection standards (for example, NFPA Standard 412, (NFPA 2020) and manufacturer’s recommendations, the testing of mobile firefighting equipment should be conducted routinely and documented.

Multiple pieces of equipment can be tested or inspected simultaneously. Mobile equipment, including but not limited to mobile foam extinguishers, firefighting vehicles, and marine craft, can be collected, tested, and cleaned and foam concentrate samples can be collected in a single location to minimize potential impacts. It is recommended that testing of mobile firefighting equipment is executed at purpose-built facilities specifically designed to capture and contain all generated foam and wastewater for treatment, reuse, or disposal.

Conditions during equipment testing should include secondary containment measures to ensure foam solutions can be captured and managed and environmental impact minimized. Alternatives to traditional testing methods may be considered, such as:

- using water or surrogate solutions for training
- testing equipment indoors
- spraying into drums or other containers
- testing within lined pits or spill containment equipment
- testing with closed-loop AFFF testing systems to minimize and eliminate discharge (FAA 2023).

Other controls include not testing during adverse weather conditions, not testing where the facility is not deemed fit for purpose, conducting a risk assessment of the activity, and minimizing foam wastewater volume generated whenever possible. As with fixed fire suppression systems, mobile equipment that complies with NFPA Standard 412 requires that the equipment produce a foam/foam solution that can be tested and compared to laboratory-analyzed solutions (NFPA 2020).

3.7.3 Training Exercises

Facilities should have specifically designed areas and structures to conduct training exercises involving flammable liquid fires and foam systems. The fire training areas (FTAs) should be arranged to contain/control the training site for the safety of the persons being trained. Control of training fires as well as applied foam and/or foam solutions is maintained by the facility design. The FTA should also be designed for collection/recovery of unburned fuels as well as the foam solution and fire water following the completion of training exercises. Conducting outside exercises during windy weather conditions should be avoided, as the foam solutions can be difficult to contain due to natural aspiration and windblown transport.

Past training exercises at airports and military installations employed large quantities of foam/foam solutions. To prevent further releases to groundwater, USDOD issued a policy in January 2016 requiring prevention of “uncontrolled land-based AFFF releases during maintenance, testing, and training activities. Current USDOD policies prohibit using AFFF with PFOS for testing, maintenance, or training exercises with the exception of shipboard activities.

Consider minimizing the volume of foam used to the greatest extent possible. If permitted by the applicable regulatory requirements for training, consider entirely discontinuing the practice of using expired legacy AFFF and modern fluorotelomer AFFF as training foam. Whenever possible, seek fluorine-free alternatives for training events; consider training with water or training foam where practicable, not Class B foam, and certainly not with Class B foam containing PFAS. Any wastewater or foam generated from training activities should be kept to a minimum and foam spraying should be restricted to target areas only (not sprayed over wide areas). Preplanning responses that deploy AFFF can identify weaknesses in both AFFF use strategies and in fuel and fire water runoff and containment. This can also identify the need for calling mutual aid early to assist with containment tactics.

Training protocols with F3s must be established. While F3 foam does not contain PFAS, some F3 foams may contain other additives or chemicals that could be harmful to the environment or human health. As such, any training involving F3s should also consider the mitigation measures established for AFFF.

3.8 Emergency Firefighting Operations

Fire response planning in advance can identify various options for firefighting and contingency planning for fire wastewater capture. Where possible and as setup allows, consider containing and recovering AFFF used for emergencies for disposal. Use mutual aid resources to assist with containing the fuel and fire water runoff should your department not have the resources available to fight the fire emergency and contain the runoff (Section 3.7). Although federal law currently does not prohibit the use of existing stocks of legacy AFFF, any discharge of foam containing PFAS to public waters can be considered a release of a “pollutant or contaminant” under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA), 42 U.S. Code § 9601, and therefore may be subject to remediation requirements.

Consideration should be given to parts of facilities not protected by the fixed foam system that could be subject to AFFF application in the event of an emergency incident and opportunity for containment of foam.

Emergency scenarios vary case by case. Industrial plant fire brigades and responding emergency crews utilize portable foam generators or monitor nozzles to apply foam to pooled flammable liquids (potential fires) or existing fires. In cases where the fire involves a fixed system, it is critical that an arrangement for containment/control of runoff is included in the design. The following are examples of how preplanning can better inform the use and containment of AFFF at an industrial facility:

- Industrial processes have many components, and only portions of the process are protected by the fixed foam systems. For example, a scrubber, or filter found within industrial smokestacks, may be part of the process that is not protected by the foam system and may be outside the discharge area where design considerations have been made for containment/control. Emergency response units may be required to apply foam/water to the location of the scrubber, outside the planning boundaries, in the event the fire that originated in the process was conveyed to the scrubber unit.
- At oil refineries, F3 may be used for small incidents and fluorinated foam reserved for the large tank fires. Fluorine-free and new generation C6 foams have been tested in large-scale tests (involving up to 40 m foam travel requirements) and could be considered suitable for application to fires involving some tank sizes and the associated dike area fires. But firefighting foam use is rapidly evolving, and as such, those responsible for tank application foam selection should refer to the latest test results from any recognized independent source (for example, LASTFIRE) to determine whether F3 could meet the performance requirements.
- On some remote industrial sites, where no immediate threat to life or property exists, and given the additional resources necessary to manage the wastewater produced, the best response may be to let the fire burn instead of applying AFFF.

3.8.1 Best Management Practices (BMPs)

BMPs are key to the use of AFFF in the most environmentally responsible manner with the goal of minimizing risk from their use. It is important to establish BMPs prior to use in an emergency so that BMP equipment, procedures, and training are already in place. Although firefighting personnel may be aware that the foams they are using contain chemicals, they may not be aware of the potential environmental effects of AFFF use. Training of firefighting personnel is important to ensure BMPs are discussed and employed consistently and effectively.

Example BMPs, adapted from the Fire Fighting Foam Coalition (FFFC 2016) are summarized in Table 3-3. Table 3-3 also includes some information from Angus Fire (2017). Users should follow BMPs to protect themselves, others, and the environment when using AFFF and other foams. Further BMP guidance can be found in other documents, such as the Best Practice Guidance developed by the Fire Fighting Foam Coalition (FFFC 2016), and the US National Fire Protection Association's NFPA 11 NFPA (2016)[692]. Users at DOD facilities have other BMPs to follow. Other industry associations such as American Petroleum Institute (API) have also issued BMPs (API 2020).

Other foams such as alcohol-resistant foams (AR-AFFF), film-forming fluoroprotein foams (FFFP), alcohol-resistant film-forming fluoroprotein foams (AR-FFFP), fluoroprotein foam (FP), and alcohol-resistant fluoroprotein foam (FPAR), as illustrated in Figure 3-2, also contain PFAS and similar precautions and considerations should be taken.

Section 3 provides supporting information for the BMPs presented in Table 3-3, as follows:

- Foam selection and storage are discussed in Section 3.6 (AFFF Procurement and Inventory).
- Use is detailed in Section 3.7 (Foam Systems and Operations).
- Planning and mitigation are covered in Sections 3.8 (Emergency Firefighting Operations) and 3.9 (Immediate Investigative and Cleanup Actions).
- Disposal is addressed in Section 3.10 (AFFF Disposal).

Table 3-3 addresses current operating procedures for selection, storage, use, planning and mitigation. For complete change-out and transition from AFFF to fluorine-free across an entire system, detailed consideration should be made regarding performance, compatibility, decontamination, treatment, and disposal.

Table 3-3. BMPs for AFFF (and Other Foams) Selection, Storage, Use, Planning and Mitigation, and Disposal (adapted from FFFC 2016)

Life Cycle	BMP
Foam Selection	1. Public safety first. Use AFFF and other fluorinated Class B foams only in the following situations: • Class B liquid fires and/or spills with significant risks to public safety or of property loss, where specific extinguishing rates and burnback times are necessary • Facilities where AFFF is required until F3 replacement that meets Mil-Spec has been approved
	2. Evaluate whether Class B foam is needed for a specific hazard, or if an alternative product, such as an F3 can provide the needed level of protection. The proper agent to use for your hazard "must be evaluated well in advance of an emergency situation" (FFFC 2016).

Life Cycle	BMP
Storage	1. Develop a foam inventory and stock tracking system documenting foam composition, date of purchase, lot number, brand, and manufacturer.
	2. “Obtain and follow manufacturers’ recommendations for foam concentrate and equipment” (FFFC 2016). The amount of foam in the system should be at least enough for the group of hazards that simultaneously need to be protected against.
	3. Designate transfer areas and store Class B foam concentrate (all foam, not only AFFF) in a covered area with secondary containment.
	4. Design storage tanks to minimize evaporation of concentrate. Label containers clearly to identify the type of concentrate and its intended concentration in solution. Keep foam within the temperature limitations provided by the manufacturer.
	5. Properly maintain foam systems to prevent accidental discharges. Conduct regular inspections of tanks, storage containers, and any associated piping and machinery. Any leaks of foam concentrate should be addressed immediately to minimize environmental impacts. Maintain records of accidental releases, including date, volume, and foam type. Be cognizant of state and local reporting requirements for releases.
	6. Corrosion is reported by some to generally not be an issue with foam concentrates, but exceptions exist. Check safety data sheets to evaluate corrosivity of your product. Manufacturers recommend stainless steel, high-density polyethylene (HDPE), or polypropylene containers for AFFF storage. Avoid using aluminum, galvanized metal, and zinc in storage tanks, piping, and handling equipment for foam concentrates (Angus Fire 2017).
	7. Ensure compatibility of foams per manufacturer specifications before change-outs. Do not mix different types or brands of foam concentrates unless all the foams are compatible. As an example, all foams that meet Mil-Spec 24385 are considered compatible.

Life Cycle	**BMP**
Use	1. Consider the firefighter and public safety first.
	2. Eliminate the use of AFFF and other fluorinated “Class B foams for training and testing of foam systems and equipment” whenever possible. Instead, use specially designed nonfluorinated, PFAS-free “training foams available from most foam manufacturers.” (FFFC 2016).Be aware that such training foams result in longer extinguishments and less burnback protection.
	3. If the authority having jurisdiction requires testing of equipment or training of firefighters using AFFF, training foams that do not contain fluorinated compounds are preferred and, in many cases, required. All foams, regardless of type, should be captured during training and testing.
	4. Evaluate firefighting strategy to determine if Class B foam is needed or if a Class A foam or just water can succeed in fighting the fire.
	5. Provide containment, treatment, and proper disposal of foam solution. Avoid direct release to the environment to the greatest extent possible.
	6. Collect, treat, and properly dispose of runoff/wastewater from training events or live fire events to the greatest extent possible. Prevent discharge to storm drains and surface water to the greatest extent practicable.
	7. Use appropriate personal protective equipment (PPE) when handling and using AFFF and identify how to decontaminate and or dispose of PPE materials and gear that come into contact with foam.
	8. “Follow applicable industry standards for design, installation, maintenance, and testing of foam systems” (FFFC 2016).
	9. Keep records of when and where foam is used to respond to incidents, including foam type, manufacturer, brand, and amount used.
	10. Make note of any sensitive receptors (for example, streams, lakes, homes, wells) identified in the vicinity of foam use and report to environmental agencies as required.
Planning and Mitigation	1. Develop and communicate documented processes for a facility or installation with the stakeholders and regulatory agencies before a release occurs. Stakeholders may include local fire department, elected officials, landowners, interested parties, and local environmental groups.
	2. Prepare runoff collection plans, equipment, and training processes for all foam and those specific to fluorinated Class B foam use.
	3. Create mitigation plans for uncontrolled releases of foam concentrate or foam solution to minimize environmental impacts (FFFC 2016).
	4. Quickly and thoroughly clean up any contaminated environmental media after foam release following established mitigation plans.
	5. Design new firefighting systems to accommodate F3s. Consider their different properties, modes of action, and effectiveness.
	6. Prioritize education, training, and preplanning to ensure the safest and most efficient use of foam and equipment during an incident.

Life Cycle	BMP
Disposal	1. Proper disposal of foam is imperative. See Section 3.10. When available, consider disposal of AFFF inventory to state collection and disposal programs. Refer to Interim Guidance on Destroying and Disposing of Certain PFAS and PFAS-Containing Materials That Are Not Consumer Products (USEPA 2020).
	2. Terminate any donation programs for expired or unused AFFF concentrate (for example, donation to fire training school). Instead, as stated above, encourage collection/proper storage/disposal of expired or unused AFFF.
	3. Monitor developments in new treatment and disposal technologies.

3.8.2 Personal Protective Equipment

The use of personal protective equipment (PPE) is highly recommended when exposure to AFFF, as well as other firefighting foams, is anticipated. A critical aspect of PPE is ensuring the proper use of the equipment. The equipment should be used correctly, maintained, and decontaminated routinely (Queensland Government 2021).

During the application or immediate cleanup of AFFF foam, the use of a self-contained breathing apparatus or positive pressure–supplied air respirator is recommended to avoid respiratory exposure. Dermal exposure should also be avoided, as skin contact can result in irritation and dryness. When responding to fires, first responders should wear appropriate turnout gear, or proximity gear per their specific department requirements.

PPE cleanup after using AFFF (as well as other foams) is discussed in the next section.

3.8.2.1 Decontamination

Although PPE will prevent initial exposure to AFFF, contamination of the PPE itself can present health risks. Decontamination of the PPE and personal hygiene are crucial preventative measures in reducing or avoiding exposure to AFFF, as well as in avoiding cross-contamination. Since there is little PFAS-specific guidance on PPE decontamination, general PPE use and decontamination approaches should be used, as discussed below.

When handling AFFF concentrate or foam, it is imperative to avoid hand-to-mouth contact. After the use or cleanup of AFFF, responders should wash hands and use other decontamination procedures to remove any residual AFFF from the skin. Responders should remove contaminated clothing and launder before reuse.

PPE should be placed in a bag and container after exposure to AFFF as well as other foams. In 2014, NFPA released its latest edition of NFPA 1851: Selection, Care and Maintenance of Protective Ensembles for Structural Firefighting and Proximity Firefighting. This standard provides guidance for proper care of firefighting protective gear as well as health hazards associated with improper maintenance or contamination of protective equipment (NFPA 2014). The standard outlines different decontamination measures for turnout gear as well as proximity gear.

Turnout gear is the general PPE for firefighting. It should be machine washed in warm water in the normal cycle. Turnout gear should be spot treated with warm water, a soft brush, and mild detergent prior to being machine washed. When hand washing and spot treating PPE, wear protective gloves—either latex or PVC— to avoid skin contact with any residual AFFF. No fabric softener or bleach should be used. The turnout gear should never be washed in home washing machines, as this practice has the potential to contaminate personal clothing. Advanced cleaning is suggested at least on a yearly basis (Avsec 2015).

Although PPE decontamination prior to reuse is important, it is equally important to recognize when decontamination is not possible. In this case, the gear should be discarded in accordance with local, state, and federal regulations.

When decontaminating or laundering PPE, the disposition of the waste stream should be considered. The potential for environmental impacts due to laundering in washing machines is not well defined, but the potential does exist. Regulatory agencies should consider including decontamination procedures when working with firefighters, refinery safety personnel, and other potential first responders to develop BMPs.

3.8.3 Initial Mitigation Efforts for Firefighting Foam

Initial mitigation efforts following a release of firefighting foam include source control, containment tactics, and recovery tactics. Each is further described in this section.

Discharges of AFFF can occur during firefighting operations, system testing, equipment malfunctions, or incidental releases. In addition to foam, a large amount of water is often applied when attempting to suppress a fire. Due to the highly miscible nature of AFFF, the main objective of the initial mitigation efforts should be to reduce the footprint of contamination by limiting the spread of foam and fire water. This is often done through various containment and recovery tactics while making sure that the release has been abated and response personnel are safe.

Specific department or facility fire wastewater management considerations may be outlined in a fire response plan, which should include information such as resources available within the facility or department fire protection jurisdiction to contain and recover fire water, protect sensitive areas (for example, public and private water systems, storm drains, surface water, critical wildlife habitat), and address safety considerations when conducting water management tactics. By using the fire response plan, first responders familiar with the content can increase the potential for a successful response while reducing or eliminating any imminent or substantial threat to human health, safety, welfare, or the environment.

3.8.3.1 Source Control

In addition to AFFF application for emergency response, accidental discharge of AFFF can occur from faulty or malfunctioning equipment such as hard-lined fire suppression systems in aircraft hangars or equipment used to apply or contain foam (for example, fire engines or storage tanks). The first step in any response is to stop the accidental discharge or release at the source by disabling or shutting off the system, if possible, and then temporarily or permanently repairing the malfunctioning equipment. By controlling the source, the impact to the environment is minimized.

3.8.3.2 Containment Tactics

Due to AFFF's miscible nature, as well as the large amount of water often applied in combination with the foam, containment tactics that prevent or minimize surface water runoff are critical during and after emergency response activities. Proper containment tactics may also reduce the footprint of the affected area to make the containment and cleanup easier. Depending on resources available to response personnel and conditions of the release, tactics such as ditching, berming, diking, damming, and blocking storm drains, culverts, or other surface inlets can help to contain runoff. When using these tactics, it is important to ensure that any digging activity will not result in breaking through a confining layer that would allow contaminated water to move more quickly into the subsurface and specifically to groundwater. Several response organizations have tactics manuals available online for review, including the Spill Tactics for Alaska Responders (STAR) Manual (AK DEC 2014) and Alaska Clean Seas Tactics Manual (Alaska Clean Seas 2017). Most manuals are targeted at tactics proposed to be conducted after a release of oil or other petroleum products, but most of these tactics will also apply to AFFF releases. General guidance, similar to this section, on containment tactics to be conducted after a foam discharge has been provided by several other organizations, including the Firefighting Foam Coalition (FFFC 2016, 2018) and the Queensland Department of Environment and Science (Queensland Government 2021).

As stated previously in this section, preplanning can greatly assist with prioritizing sensitive areas or locations that need protection during the mitigation or response effort after an AFFF discharge, as well as the resources necessary to succeed with this strategy. The containment tactics used and resources required will differ among sites. Preparedness can be increased by identifying potentially sensitive areas. Also, designing infrastructure such as aircraft hangars with foam-applying fire suppression systems so that the discharged foam is automatically directed to storage tanks or containment structures can minimize the need for any cleanup. The DOD has provided guidance via Engineer Technical Letters (USACE 2018) that address containment/disposal system design for AFFF discharges from open systems (such as nozzle and deluge sprinkler systems) and closed systems (in which individual sprinkler heads are activated only by heat of a fire).

Because no single set of containment tactics is going to be applicable to all facilities or departments where a foam discharge occurs, it is important for each user to conduct preplanning to identify solutions that fit its facilities, objectives, and specific response scenarios.

3.8.3.3 Initial Recovery Tactics

Recovery tactics can differ depending on the amount of AFFF released, as well as whether the AFFF is discharged during firefighting operations or accidentally (for example, from malfunctioning equipment). Collection of large volumes of AFFF concentrate or the 1%, 3%, or 6% AFFF mixture combined with water could require the use of mechanical devices such as pumps or vacuum trucks, while absorbent material might suffice to clean up after a smaller release. The AFFF and water mixture has a low flammability and a high flash point, so there is no need to use intrinsically safe pumps or mechanical devices unless other, more flammable compounds are present in the fire water being recovered.

It may be beneficial to remove affected AFFF saturated materials such as soil and vegetation to reduce or eliminate surface or subsurface migration of potential contaminants. Removal of contaminated media may reduce or eliminate the need for additional investigation and cleanup in the future; however, focus during the initial mitigation effort should be on the more easily recoverable media such as affected waters or slurries. Initiating recovery tactics as soon as possible after a release of AFFF will greatly reduce the footprint of PFAS-contaminated materials and lower the cost of the total mitigation effort.

3.9 Immediate Investigative and Cleanup Actions

A series of immediate investigative actions can be taken after the use of AFFF at the site of a fire to determine the level, nature, and extent of the contamination. First responders should collect, to the best of their ability, information regarding the volume of AFFF discharged, its concentration, active ingredients, and discharge location information.

Information about actions to be taken after the immediate actions is included in Section 10, Site Characterization; Section 11, Sampling and Analysis; and Section 12, Treatment Technologies.

Traditional field-screening methods used for other types of contaminants (for example, PID field screening for petroleum) are not effective for PFAS due to their unique chemistry, generally low volatility, and lack of development of colorimetric or reactive chemistry technologies. Some efforts have been made to develop mobile analytical laboratories, which are covered in Section 10.3.1.3 of this document.

3.9.1 Visual Site Delineation

Visual site delineation refers to outlining the affected area of contamination based on visual clues, such a visible foam and wet ground, as a guide. The extent of foam should be marked using survey tape, lathe, and pin flags placed to identify locations of AFFF contamination. This technique of determining the initial expanse of the contamination is simple to perform directly after a discharge and can be useful for reference in future testing on the site. In addition, photographs of the site taken during or immediately after the incident can be used to determine the extent of AFFF impacts.

3.9.2 The Shake Test

The shake test is an informal qualitative field-screening method that provides a visual analysis of the site contamination. The shake test can apply to both water and soil-water solutions. In the shake test, a small sample (10–25 mL) is collected on site by the field personnel and shaken. After it is shaken, if there is foaming in the sample, it should be noted and then submitted for analysis (Transport Canada 2017). Photographs of the samples may be helpful. If AFFF foam was used to fight the fire, then the presence of foam strongly suggests the sample may be contaminated with PFAS. This test is a good indicator for high concentration contamination. It may not be able to detect lower concentrations of contaminants, so lab testing may still be required. This may be true of soil and water samples taken around the foam application location where the shake test does not show foaming but the sample media may still have PFAS above background in it.

3.9.3 Initial Investigative Sampling

Investigative sampling is used to determine the nature and extent of contamination, including concentrations at and surrounding release areas. Initial investigative sampling can help to determine whether additional characterization is necessary, in addition to informing the need for and extent of interim or permanent remedial actions. Combining the information gained from investigative and confirmation sampling with information from a CSM will inform project managers as to whether further site characterization and remediation or mitigation efforts are needed. See Section 5, Environmental Fate and Transport Processes, Section 10 and Section 12 for additional information on the actions that may be needed following initial response.

3.9.4 Interim Removal

Following the information gathering described above, or possibly prior to initial investigative sampling, additional source control can be achieved through removal of soils that are expected to be highly contaminated. During an initial removal action intended to target PFAS hot spots, soil excavation can be guided by shake tests (Section 3.9.2). An interim removal is not necessarily designed or expected to remove all contamination but can help to reduce the migration of PFAS into other media, including groundwater and surface water. After this initial removal effort, it may be appropriate to hire an environmental professional to perform further mitigation efforts. To determine how to dispose of the soil, see Section 12.

3.9.5 Confirmation Samples

Once removal actions take place, confirmation samples are taken to confirm that an excavation or interim removal successfully removed the soil contamination that exceeds applicable regulatory or risk-based levels. If confirmation sampling determines that soil contamination still exists at levels of concern, additional removal actions or other types of remediation or mitigation may be required. The type, number, and distribution of confirmation samples is determined on a site-specific basis according to local regulatory guidance.If confirmation sampling is delayed due to weather events—for example, a rainfall event—the results from such sampling should be interpreted carefully.

3.10 AFFF Disposal

BMPs recommend that volumes of AFFF foam concentrate be carefully monitored and recorded at each storage location, from fire trucks to suppression systems to storage containers (see Table 3-3). Weights of other AFFF system components requiring disposal should be similarly observed. Disposal certificates for materials bound for removal should indicate volumes of AFFF concentrate or solution or weights of system components or debris, as applicable. Total volumes or weights generated for disposal should match that indicated on disposal certificates.

Disposal of AFFF concentrate represents a significant challenge for any owner of firefighting foam concentrates. The disposal of AFFF concentrates through standard disposal options may carry risks. Practitioners should be aware of possible disposal options, best management practices, and disposal hierarchy, as explained by USEPA (USEPA 2020). Manufacturers' product literature and local regulatory agencies should be consulted for information regarding the specific foam concentrate to be disposed. Some disposal options that are currently available for AFFF concentrates and AFFF-impacted natural media are presented in USEPA's *Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances* (USEPA 2020). Additional information can be found in Stoiber, Evans, and Naidenko (2020) and Aleksandrov et al. (2019).

As of February 2021, the USEPA interim PFAS destruction and disposal guidance (USEPA 2020) is closed for public comment. EPA plans to update the interim guidance by December 2023. Currently available AFFF concentrate disposal options are briefly presented below and in Table 3-4. Table 3-4 also presents advantages and disadvantages associated with each disposal method and new disposal technologies that were under development when this table was prepared. The disposal options that are currently available for materials impacted with dilute AFFF wastes are presented in Section 12, and include stabilization and landfilling, incineration, and deep well injection.

As stated in the USEPA interim PFAS destruction and disposal guidance (USEPA 2020), one option for addressing disposal concerns related to environmental releases of foam, byproducts, or other possible releases is to store AFFF in warehouse storage to provide time for completion of studies for destruction, disposal, or stabilization of the AFFF. Stakeholder concerns regarding AFFF waste disposal practices are presented in Section 13.1.11.

Each of the currently available disposal options presented below and in Table 3-4 has different advantages and disadvantages that the practitioner should consider when deciding how to dispose of AFFF concentrates, including availability, cost, effectiveness, and potential long-term risks associated with nondestructive disposal options.

3.10.1 Stabilization and Landfill Disposal

Waste stabilization and landfilling is a nondestructive disposal methodology wherein waste, including AFFF concentrates, are mixed with stabilizing materials (for example, Portland cement) and disposed at a landfill that is licensed to accept and manage these wastes. This disposal method is nondestructive in that the waste is not destroyed but immobilized and encapsulated to prevent exposure and reduce potential mobility. Ultimately the stabilized and landfilled AFFF concentrate is managed with other wastes disposed of at the same landfill through landfill best management practices (for example, liners, leachate collection, cap management, groundwater monitoring, etc.). Stabilization and landfill disposal is an accepted waste management strategy in some states, though the long-term stability of stabilized AFFF concentrate is not well understood.

Practitioners with AFFF concentrates requiring disposal should collaborate with their local or state agency waste management personnel, as applicable, to determine current availability and acceptability of stabilization and landfill disposal as a waste management practice. AFFF concentrate bound for disposal should be properly documented (for example, a proper manifest or bill of lading) as a best practice and in compliance with state and federal transportation regulations (as discussed in Section 3.6.2). After the concentrate product has been disposed of, a certificate of disposal may be generated by the disposal facility, transmitted to the product owner, and retained by the disposal facility. This certificate of disposal may be transmitted to the state regulatory agency for review and maintained on file by the product owner.

3.10.2 Incineration

Incineration is a destructive disposal technology wherein AFFF concentrate is destroyed, or mineralized, through the application of heat. Heat is applied to the AFFF concentrate at incineration facilities that have the capability to manage high temperatures and residence times required to destroy AFFF concentrate, as well as vaporized combustion products (flue gases) that are captured and/or further incinerated. Most AFFF concentrate has historically been disposed of using incineration in the United States (FFFC 2016). However, the effectiveness of incineration, and the temperature and time conditions required to achieve complete PFAS destruction, are not well understood (USEPA 2020). Legal, technical, and political challenges to incinerating AFFF exist based on gaps in research on the effectiveness of incineration (Earthjustice 2020). For example, the New York State DEC prepared a sampling report in 2021 near one incineration facility in response to concerns about emissions from the facility (NY DEC 2021). USEPA researchers are currently studying PFAS incineration, sampling and analytical methods development, and industrial field sampling. Thermal stability of PFAS, the ability to fully capture and identify PFAS and their thermal decomposition byproducts, and the efficacy of emission control technologies are areas of targeted research (USEPA 2020). The NDAA for fiscal year 2022 (https://www.congress.gov/bill/117th-congress/senate-bill/1605) establishes a temporary moratorium on incineration of AFFF generated by DOD. The temporary moratorium began no later than 120 days after enactment of the NDAA FY22 (4/26/2022) and will be in place until the Secretary of Defense issues guidance for implementing the USEPA’s destruction and disposal guidance (USEPA 2020) or the USEPA Administrator publishes a final rule in the Federal Register regarding destruction and disposal. The DOD published a memo about the temporary prohibition on April 26, 2022 (USDOD 2022).The DOD published a memo with interim guidance about destruction or disposal of materials containing PFAS on July 11, 2023 (USDOD 2023).

This technology is currently the only known AFFF destruction technology in widespread use, though the efficacy of incineration as an effective disposal option for AFFF concentrate is an area undergoing further study (USEPA 2020). At the time of publication there are a number of studies ongoing to evaluate destruction temperatures and treatment time required to achieve complete AFFF destruction, the potential to generate products of incomplete combustion, flue-gas analyses to assess mobilization of AFFF concentrates, and other risk factors. Owners of AFFF concentrates requiring disposal should consider contacting their local or state agency waste management personnel, as applicable, to determine current acceptability of incineration as a disposal practice prior to disposal.

3.10.3 Deep Well Injection

Another disposal approach, available in some states, is to dispose of AFFF concentrate through deep-well injection. In some cases, disposal via landfilling of a stabilized concentrate or deep well injection at a licensed hazardous waste management facility has been used. This disposal option eliminates discharges to surface water and shallow groundwater, similar to stabilization and landfilling, but does not destroy or degrade disposed wastes. Deep well injection is an available option that is being used given the currently limited number of disposal options for AFFF concentrate. Class I deep injection wells, as defined by USEPA, accept both hazardous and nonhazardous liquid wastes (USEPA 2019), including AFFF waste materials such as dilute AFFF (fire water) and AFFF concentrates. The USEPA has published guidance on the requirements for the use of deep injection wells, including siting, construction, operation, monitoring, testing, record keeping, reporting, and closure (USEPA 2019). The USEPA has also studied the risks associated with underground injection wells (USEPA 2001), and these risks are documented for consideration by generators prior to disposal of AFFF concentrates through deep-well injection.

3.10.4 Potential Future Disposal Technologies

The currently available disposal options for AFFF waste are limited and carry inherent unknowns in terms of long-term reliability. This is of particular importance when considering nondestructive disposal means such as stabilization and landfill disposal and deep well injection. These unknowns translate into short- and long-term risks for the practitioner. Additional disposal options may be available in some areas (for example, deep well injection) for AFFF concentrate wastes and AFFF-impacted materials. Alternate treatment and disposal technologies are presented in Section 12. New treatment and disposal technologies are an active area of research and development by a number of groups; some are presented in Table 3-4. All technologies will require extensive evaluation to ensure they are fit-for-purpose.

Table 3-4 PFAS Waste Materials Disposal Options

Current as of October 2022

Current Disposal Practice	Advantages	Disadvantages
Stabilization and Landfill Disposal (Section 3.10.1)	1. AFFF concentrate mass is encapsulated and immobilized in a stable form 2. Disposal is at a licensed landfill with monitoring programs and leachate collection systems designed to ensure disposed mass remains controlled 3. Long-term management of the disposed waste is part of the overall landfill management and monitoring program	1. Disposed AFFF concentrate mass remains in place with no known and documented destruction mechanisms 2. Risks associated with comingled waste disposed of at the waste management facility 3. Long-term testing of stabilized PFAS waste materials under landfill conditions is limited. Some studies are available (CONCAWE 2016; Oliaei et al. 2013; Weber et al. 2011) 4. PFAS mass from disposed wastes can form mobile leachates, which require long-term collection, management, and disposal (Stoiber, Evans, and Naidenko 2020) 5. Some PFAS may be emitted by the landfill gas collection and management system
Deep Well Injection (USEPA, 2019; USEPA, 2020; Marine 2020) (Section 3.10.3)	1. AFFF concentrate mass is injected deep underground in previously defined tectonically stable strata 2. Waste is injected well below drinking water aquifers, reducing potential for future impacts to drinking water resources 3. Waste immobility and lack of potential for unacceptable migration must be documented prior to waste injection 4. Long-term management of the injected waste is the responsibility of the operator while the disposal facility is in operation	1. Disposed AFFF concentrate mass remains in place with no documented destruction mechanism known 2. Waste materials are injected with no modifications or additives to reduce migration potential or enhance degradation 3. Deep well injection facilities are generally operated with limited mandated monitoring to document lack of long-term waste migration 4. The long-term stability of injected wastes is undocumented
Incineration—General (Section 3.10.2)	1. Incineration (at properly licensed and operated disposal facilities) is the only disposal technology currently available that has the potential to result in the destruction of PFAS 2. PFAS destruction through incineration has been documented in laboratory studies (e.g., Aleksandrov et al. 2019; Khan et al. 2020) but known studies analyzed only for a subset of PFAS 3. PFAS destruction reduces/eliminates future risk 4. Some incineration facilities maintain successful track records of operating within permit requirements based on system performance monitoring data collection	1. The efficacy and operational requirements of incineration are currently under question and require additional study (USEPA 2020) 2. Existing laboratory experiments on the incineration of PFAS do not address the full spectrum of potential PFAS byproducts that could form during incineration (Stoiber, Evans, and Naidenko 2020; USEPA 2020) 3. Current regional and local moratoria exist in some locations against incinerating PFAS waste. Practitioners should confirm disposal vendor licensing and operational status prior to shipping AFFF concentrate for disposal
Incineration—Municipal	1. Municipal incinerators are readily available and offer a comparatively low-cost disposal option if operated at sufficient temperatures and residence times and if equipped with appropriate emissions controls	1. Municipal incinerators may not be permitted to accept AFFF concentrate for disposal 2. Temperatures, residence times and emissions controls may not be adequate to fully degrade PFAS 3. Potential for partial decomposition of PFAS to shorter carbon chain-length PFAS (USEPA 2020) 4. Existing laboratory experiments on the incineration of PFAS do not address the full spectrum of potential PFAS byproducts that could form during incineration (Stoiber, Evans, and Naidenko 2020; USEPA 2020)

Current Disposal Practice	Advantages	Disadvantages
Incineration—Hazardous Waste	1. Some specialized incinerators exceed minimum temperature required 2. Some are designed to handle flue gases and scrubber wastes 3. Generators may be able to obtain a disposal certification from the incineration facility	1. Temperatures, residence times, and emissions controls may not be adequate to fully degrade PFAS at some standard commercial facilities 2. Potential for partial decomposition of PFAS to shorter carbon chain-length PFAS (USEPA 2020) 3. Difficulty handling high-water content wastes
Incineration—Cement Kiln	1. Temperatures and residence times in excess of minimum required (1100°C and 2 seconds) 2. Effective permanent capture of fluorine 3. No extra energy required above normal kiln processing	1. Potential for partial decomposition of PFAS to shorter carbon chain-length PFAS (USEPA 2020)
Experimental Disposal Technologies (Section 3.10.4)		
Electrochemical Oxidation (Le et al. 2019; Ensch et al. 2020)	PFAS is degraded in a closed-cell reactor using metallic electrodes and electrical current. Several different types of electrodes (titanium oxide, boron-doped diamond, etc.) have degraded some PFAS to varying degrees of success and several studies were underway in 2020. In previous laboratory-scale studies, PFAS destruction was achieved, though at relatively low throughput rates. This disposal technology is applicable to liquid waste streams only.	
Enhanced Contact Plasma Reactor (Singh et al. 2019)	PFAS are degraded in a closed system using water, electricity, and argon gas to degrade PFAS through a series of sequential destruction steps. At laboratory scale the destruction of PFAS was observed within their ability to measure, limited by analytical method detection limits. Air Force Civil Engineering Center (AFCEC) and Clarkson University were field testing this technology at Wright-Patterson Air Force Base, Ohio in 2020.	
Alkaline Hydrothermal Treatment (HaLT) (Wu et al. 2019)	Perfluorooctane sulfonate (PFOS) and potentially other PFAS are degraded through the application of hydrothermal conditions (condensed water at high temperature [200–350 °C] and high pressure [2–16.5 MPa]) to solutions amended with NaOH. Initial studies document PFOS destruction within 90 minutes. Expanded laboratory studies continue to investigate efficacy over a broader range of PFAS compounds.	
Supercritical Water Oxidation (SERDP-ESTCP 2020)	Supercritical water oxidation at high temperature (greater than 373 °C) and high pressure (greater than 22 MPa) has been demonstrated to degrade PFAS. Battelle Memorial Institute has patented a process called PFAS Annihilator to apply this technology for the destruction of PFAS. In addition, an ESTCP-supported study at Duke University began in May 2020 to demonstrate the efficacy of this technology at higher throughput rates (approximately 907 kg of waste material per day).	

3.10.5 Fire Water and Flush Water Containing AFFF

Fire water produced during training or emergency response, as well as flush water produced during the rinsing of firefighting systems and equipment, may be managed and disposed of as a generated waste because these waters contain dilute concentrations of PFAS. Practitioners may consult with local regulatory agency personnel ideally prior to the generation of fire- and flush water so that there is a good understanding of local laws and regulations governing disposal. Standard practices for foam containment and cleanup should be developed prior to use such that response teams have the needed equipment and training before an event occurs; Table 3-1 provides additional information for BMPs. Some fire water disposal options are focused on reducing the volume of wastewater through concentration and disposal of the generated concentrate via incineration, landfilling, stabilization, or other mechanisms. See Section 3.10.1 for comments related to these disposal methods. Widely used treatment methods, as presented in Section 12 are as follows:

- granular activated carbon treatment
- discharge to and treatment at a wastewater treatment plant
- pumping AFFF-impacted fire water into watertight, secure containment basins and allowing the water phase to evaporate, leaving behind a solid or semi-solid material containing the AFFF concentrate. The remaining material is then disposed of at a certified waste management facility (USDOD 1997). This method is an option only in some localities and where climatic conditions are favorable.

3.11 Firefighting Foam System Replacement

The AFFF application design is specific for each foam and use case and system design can vary significantly by location, manufacturer, foam product, and system objective. Changing between foam types or application objectives could require a complete system review and, potentially, redesign and modification of system components to meet the new objectives or material and performance requirements. When objectives or requirements are changed, each subject system should be evaluated and modified individually to ensure that operational objectives are met.

Procurement at U.S. airports is primarily driven by regulatory performance requirements, notably the DOD Mil-Spec, MIL-PRF-24385, as well as FAA requirements (ACRP 2017). DOD recommends complete replacement of the required AFFF concentrate supply and rinsing of the storage and discharge system prior to refilling with a different concentrate product (USDOD 2017). This not only prevents any unforeseen incompatibility issues, but also greatly reduces possible cross-contamination and the uncertainty of AFFF formulations (PFAS profile and content).

Applicable replacement products standards include NFPA Standards 11 (NFPA 2016) and 16 (NFPA 2019) for foam water sprinkler and foam water spray systems and NFPA Standards 1901 (NFPA 2016) and 412 (NFPA 2020) for equipment.

3.11.1 Replacement Products

Replacing foams and foam systems generally follows four steps:

1. Assess and understand the specific hazards and application objectives.
2. Ensure that foam product to be adopted is listed and approved for use on the specific assets that are being protected and the hazards that that are being mitigated.
3. Ensure that the foam product storage system and the foam/water application system meet product storage (for example, materials compatibility and storage temperature), proportioning, and application requirements.
4. Ensure that the selected foam product(s) meet applicable requirements (Requirements are based on where and how the foam is being used and rely on sector-specific standards such as Mil-Spec, Underwriters Laboratories (UL), or Factory Mutual compliance). These organizations audit manufacturers to ensure compliance with their standards.

Where two or more foam products meet applicable performance requirements, the foam with the best environmental performance may be considered for use. Alternatives currently available as replacement products for legacy AFFF include products discussed in the following sections.

3.11.1.1 Fluorine-Free Foams (F3)

Most foam manufacturers now produce Class B F3s. Performance of these foams should be evaluated carefully as future purchasing decisions are made. As of spring 2023, there are no military-specified F3s approved for use on Class B fires at federal- and FAA-regulated facilities that require Mil-Spec–compliant AFFF. Approved and certified military-specific foams are expected to be available and listed on the DOD Qualified Products Database by the Fall of 2023. But a mandate within the FAA Reauthorization Act of 2018 (enacted October 5, 2018) directs the FAA to stop requiring the use of fluorinated foam no later than 3 years from the date of enactment (October 4, 2021), so F3 use is anticipated at FAA-regulated facilities in the near future (FAA 2018).

There continues to be robust discussion regarding the replacement of AFFF products with F3 formulations. For example, the organization IPEN has published a document titled *Fluorine-Free Firefighting Foams (3F): Viable Alternatives to Fluorinated Aqueous Film-Forming Foams (AFFF)*, which states that F3 products are as effective in combating Class B fires as AFFF and concludes that because of the lower environmental impact of F3 products, the use of AFFF should be discontinued (IPEN 2018). The Fire Fighting Foam Coalition (FFFC) produced a three-page document responding to the IPEN paper, which discusses technical details regarding differences in foam performance for certain types of Class B fires and performance standards (as opposed to composition standards) that continue to necessitate the use of AFFF or other fluorochemical products for certain hazards. Additional challenges to the replacement of AFFF with F3 foams are also described in the FFFC document (FFFC 2018).

3.11.1.2 Modern Fluorotelomer Foams

If it is determined that the performance of a fluorinated Class B foam is required for a specific hazard (for example, the federal regulation requiring AFFF use for military applications, at FAA-regulated airports, and/or other high hazard Class B fires and potential incidents), users should purchase modern fluorotelomer foams. Most foam manufacturers have transitioned to the production of only short-chain (C6) fluorosurfactants, so it is likely that any AFFF bought today meets that requirement. But foams made with only short-chain (C6) PFAS may still contain smaller quantities (parts per billion) of PFOA and PFOA precursors as byproducts of the manufacturing process. This should be confirmed with the supplier.

Although there are currently mandated specifications requiring the use of fluorinated foams at airports and military installations, users should be aware that some compounds in modern fluorotelomer foams are regulated by several states and are known to have probable effects on human health (Section 7.1). Use of these foams may be restricted to emergency situations only and not for use in firefighting training activities. Local and state regulations may require reporting of their release, including emergency use. Section 3.12 discusses the current state of regulations on AFFF use.

3.11.1.3 Replacements, Certifications, and Alternatives Assessments

Several efforts are underway to evaluate F3 AFFF replacements for environmental and human health effects, as well as performance effectiveness. SERDP and ESTCP programs continue to “fund several research and development projects to evaluate performance, lifecycle impacts, and health and safety implications of commercially available, non-fluorinated alternatives.” For example, Jones et al. (2022) examined the direct lethal effects of seven F3 and a PFAS-containing AFFF on 14 aquatic species using a series of lethal concentration (LC50) tests. Across all aquatic species tested, they discovered that exposure to at least one F3 was more or as toxic as exposure to the PFAS-containing AFFF. This illustrates that more research is needed to understand new F3 formulations to ensure they are not regrettable substitutions. Additional information regarding PFAS toxicity, data gaps, and research needs is presented in Section 7.1. The DOD SERDP program has invested heavily in these efforts; representative studies supporting these efforts are listed in Section 3.13.

In related efforts, some organizations have developed certification processes to help consumers understand which products are considered “PFAS-free” (see Section 2.5.3). For example, Clean Production Action developed the first-ever ecolabel for firefighting foam products via their GreenScreen certification process, which identifies products as eco-labeled but does not include a release of liability. They worked with a technical review team of scientists, firefighting foam researchers, and governments to ensure the PFAS-free standard is protective, achievable, and supports purchasers to choose foam products that are safer and better for the environment. Clean Production Action defines PFAS-free as zero PFAS intentionally added to the product and PFAS contamination in the product less than 0.0001 percent by weight of the product (1 part per million) total organic fluorine as measured by combustion ion chromatography. There are currently more than two dozen certified firefighting foam products available. Go to https://www.greenscreenchemicals.org/certified/fff-standard for more information.

Alternatives assessments have been another mechanism to further evaluate F3 alternatives in terms of regrettable substitution. The first-ever alternatives assessment for AFFF (Wood Environment & Infrastructure, 2020) was completed for the European Commission and European Chemicals Agency. This assessment included an evaluation of substances in formulation, a market analysis, emissions and hazards evaluation, remediation costs and technology, an analysis of alternatives and socioeconomic impacts, and regulatory management options. As a result, a Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) restriction proposal for AFFF was submitted in 2022. Tickner (2022), funded by SERDP, completed an alternatives assessment for AFFF. The assessment focused on understanding alternatives assessments completed, supporting assessment and decisions about substitutes regarding “safer” and “sufficient performance,” and supporting needs related to adoption. Tickner (2022) developed six guiding considerations, including:

- “Determine the function of the chemical of concern for the specific application. Understand this function within the production chain.
- Define the application-specific use scenario(s). Identify alternatives that are fit for that particular purpose.
- Establish and/or use performance standards independent of the standards dependent on using chemicals/materials of concern. Adjust based on available alternatives or alternatives on the horizon.
- Use a range of performance standard benchmarks, e.g., ‘inadequate’ to ‘sufficient’ to ‘best in class.’
- Consider technical performance separately from technical feasibility.
- Consult stakeholders for determining acceptable tradeoffs between performance results and other elements such as environmental health and safety.”

3.11.2 System Decontamination and Sampling During Foam Replacement

The replacement of Mil-Spec legacy foam with the modern foams requires review of system components, particularly the proportioning system, to ensure that appropriate system performance will be maintained. During foam replacement, a thorough clean-out of storage tanks and associated pipework is highly recommended prior to filling with replacement foam concentrate. There is potential for PFOS and PFOA contamination from legacy AFFF, as described in Section 3.1, and from PFOA and other PFAS from fluorotelomer foams. For nonmilitary applications, legacy AFFF and replacement modern foams may not be compatible. In these cases, the foam manufacturers should be consulted when a foam change is required and current best practices for foam replacement, system decontamination, and verification sampling should be considered. The degree of cleanliness required and the cost balance between cleaning and replacing system components should be considered during the planning phase of a foam concentrate change-out event.

Currently, there are no regulatory guidelines or requirements pertaining to the clean-out of AFFF firefighting systems when foam concentrates containing legacy foams are replaced with alternative foams; however, local and state governments and other organizations continue to develop policy and guidance on replacing foams. DOD (and other foam users) have performed a triple water rinsing step after the legacy AFFF is removed. The rinse water is containerized and managed as a waste material as presented in Section 3.6.2. After the rinse water is removed, the modern fluorotelomer AFFF concentrate is added to the system and the system is function tested and placed back into service. Specific department or facility fire wastewater management considerations may be outlined in the facility or installation spill response plan, which should include information and resources available within the facility or on the installation to contain and recover AFFF-containing fire water to protect the environment. Proprietary cleaning solutions and coagulants have also been used for AFFF clean-out (CTDEEP 2022). These methods have been compared to the triple water rinse. No single cleaning method has yet been proven to be 100% effective in eliminating residual PFAS concentrations (CTDEEP 2022). Use of proprietary methods is more costly than triple water rinse, but these methods are more effective at reducing PFAS concentrations (>99% compared to approximately 95% removal) (CTDEEP 2022). Organizations should check with local and state regulatory agencies regarding local policies and guidance for foam change-out and system clean-out requirements or recommendations. Sampling of rinsate to ensure that residual contamination has been removed may be considered before adding replacement foams, and sampling of replacement foams that have gone through the system may provide the best assurance that PFAS will not continue to be released when the systems are used.

3.11.3 AFFF Transition Planning

Protocols around transition planning and execution of foam change-out are becoming ever more important to understand. Several factors need to be carefully considered when F3 alternatives, including but not limited to:

- What will the foam be used for and max volume of fuel source handled?
  - Fuels fires and max volume (large atmospheric storage tanks or other)
  - Chemical fires and max volume (large atmospheric storage tanks or other)
  - Other
- What are the current performance specification requirements for the foam?
  - Mil-Spec
  - Other
- What application and application technique are anticipated?
  - Fire suppression system
  - Fire response vehicles
  - Industrial fire extinguisher
  - Other
- What water type is used for mixing?
  - Fresh water (compatible with most foam products)
  - Salt water (incompatible with some foam products)
- What other types of foam characteristics should be considered? (NFPA 2020)
  - Viscosity of the foam concentrate (Newtonian and thixotropic)
  - Suitability for use with existing proportioning hardware
  - Homogeneous mixing of concentrate with water
  - Compatibility with materials in the system (for example, plastic, rubber seals, metals)
  - Stability of foam concentrate or premix solution (separation, stratification, sedimentation)

- Suitability for use on the flammable liquids in question
- Suitability of application method (aspirated, non-aspirated, forceful, gentle)
- Extremes of ambient temperature that may be encountered in an incident
- Suitability of the expansion ratios produced by existing equipment for effective firefighting performance
- Suitability of the application rates produced by existing equipment for effective firefighting performance
- Suitability in specific climate (extreme ambient temperatures, both high and low)

Table 3-5 (provided as a separate Excel file) is presented to provide example case studies for transition planning and execution. Case studies from the aviation industry and the oil and gas industry are provided. Case studies also vary by geography to illustrate potential variability by country. They are provided only as examples of how sites are implementing transition planning, but are not intended to represent guidance to be applied at other sites. The following items are included in the table:

- foam procurement, including selection criteria used to evaluate and select alternatives
- system decontamination and sampling, specifically how replacement versus clean-out was evaluated, how and whether sampling was conducted, and the definition of “clean”
- treatment and disposal, including type of cleaning reagent, waste streams generated, and how they were managed.

Because there are currently no federal or state standards on how much residual fluorine contamination in replacement foam is acceptable, each foam user is responsible for determining whether sampling and analysis of the replacement foam is necessary, and if sampled and analyzed, if the cross-contamination of replacement foam is considered acceptable for their use.

3.11.3.1 AFFF Replacement and System Clean-out

Both system replacement and system clean-out are options when transitioning to F3. There is currently no known standard practice for AFFF system clean-out procedure that is widely recommended by state or federal regulatory agencies. However, system clean-out using triple water rinse has been used by the U.S. Department of Defense, and hot water rinse (<100° F) is approved for use in some states (for example, Connecticut and New York) and is recommended in an article published by the International Fire Fighter website (Preiss 2022). U.S. vendors are developing clean-out methodologies that may be more effective than currently used methodologies—for example, rinsing with low- or high- temperature solvents or acids. Most methodologies are currently being performed as demonstration projects, are not widely used, and have not been proven on a wide scale as of the publication of this document.

When selecting a methodology for cleaning out a system, practitioners should aim to achieve the maximum level of clean-out to minimize potential for future PFAS release when the system is deployed, considering both objectives and costs. It’s important to understand that more aggressive clean-out procedures will generally be more expensive and generate more waste that will require proper management and disposal. However, inadequate system clean-out may result in the presence of residual AFFF, which may contaminate new F3 with PFAS when the system is refilled.

DOD recommends a triple rinse using water (heated or unheated) that is employed after the old AFFF foam has been drained from the system and containerized. After the system is drained, the system is iteratively rinsed and drained with water to flush out accessible AFFF residuals, and each successive rinse water volume is containerized for management and disposal (USDOD 2018). During each successive rinse, the system is completely filled with rinse water and allowed to sit for some period of time. The State of Connecticut recommends a sitting time of 30 minutes with hot water or 1–2 hours with cold water for municipal systems such as trailers and trucks (State of Connecticut 2022). Note that there are no established standard guidelines for cleaning procedures due to the immense variety of foam delivery systems for which the procedures can vary greatly even among the same manufacturer. All rinsing fluids and other waste generated during the system clean-out process should be containerized, labeled, and managed for proper future disposal. After the system has been cleaned out and rinse waters have been completely drained, new foam concentrate can be added. The practitioner should be aware that changing foam products may necessitate changes to system components, such as proportioners and discharge nozzles.

Foam change-out practitioners should also be aware of and take measures to mediate potential hydrogen sulfide generation in rinse waters that are improperly stored (Sheinson and Williams 2007). Hydrogen sulfide can be generated when foam contains sulfate (such as PFOS) or the water source itself contains sulfate. As a result, hydrogen sulfide may be in foam change-out rinse waters that are stored in sealed containers and that are allowed to transition into anoxic conditions. The hydrogen sulfide is generated through anaerobic microbial transformation of sulfate in the rinse water to sulfide followed by complexation of sulfide and hydrogen. Hydrogen sulfide generation can result in risk to site workers, particularly if starting sulfate concentrations in the rinse water are high. Regular inspection of stored rinse waters is necessary to detect any potential hydrogen sulfide generation, allowing for early implementation of mitigation steps.

3.12 Federal, State, and International Regulations and Guidance

3.12.1 Overview

This section summarizes representative information on the regulation of PFAS-containing firefighting foams (AFFF). Although federal law currently does not prohibit the use of existing stocks of legacy AFFF, any discharge of foam containing PFAS to public waters can be considered a release of a “pollutant or contaminant” under CERCLA, 42 U.S. Code § 9601, and therefore subject to remediation requirements. In February 2019, the USEPA announced in its PFAS Action Plan that the agency is beginning to evaluate designating PFOA and PFOS as “hazardous substances” through one of the available statutory mechanisms, including potentially CERCLA Section 102 (USEPA 2019). In October 2021, the EPA published the *PFAS Strategic Roadmap: EPA’s Commitments to Action 2021-2024* (USEPA 2021). The USEPA’s stated goals for addressing PFAS are focusing on research, restriction, and remediation. The strategic roadmap includes actions across the different divisions of USEPA. More information about USEPA’s actions in 2021 to address PFAS are available on their website (USEPA 2021).

As of February 2021, 18 states have established restrictions on the use of AFFF, ranging from limitations on training, notification of PFAS content and/or release, storage, and firefighter personal protective equipment (PPE) (Horst et al. 2021). AFFF use is explicitly regulated by some states, such as the State of Washington and the State of New York (Table 3-6); however, other states regulate PFOA, PFOS or their salts, and other PFAS in AFFF as hazardous substances or hazardous waste. These regulations effectively limit the storage and/or environmental release of legacy AFFF (both legacy PFOS AFFF and legacy fluorotelomer AFFF), as well as potentially triggering cleanup actions. Similar bills, banning the use of AFFF for testing and training, have been passed in other states such as Arizona, Colorado, Georgia, Kentucky, and Minnesota.

Examples of hazardous substance and hazardous waste regulations, as well as other federal, state, and international guidance pertaining to AFFF, are presented below. For more information pertaining to the regulation of PFAS, see Section 8. This section addresses only regulations related to AFFF.

Table 3-6. Representative state AFFF regulatory and legislative activity

State	Regulation or Bill	Initial Effective Date	What is Regulated?	Specific Requirement	Reference

State	Regulation or Bill	Initial Effective Date	What is Regulated?	Specific Requirement	Reference
New York	6NYCRR Part 597	March 2017	PFOS, PFOA, and Class B foams	PFOS and PFOA are hazardous substances. Storage and registration requirements for class B foams if those foams contain at least 1% by volume of PFOS and PFOA (acid and salt) and prohibit the release of 1 pound or more of each into the environment during use. If a release exceeds the 1-pound threshold, it is considered a hazardous waste spill and must be reported. Clean-up may be required under the state's superfund or brownfields program (NYDEC 2017). New York's Chemical and Bulk Storage regulations may also trigger further registration and storage requirements for foams that contain one of the four PFAS designated as hazardous substances (NY CRR Parts 596-599).	(NY DEC 2017)
Washington	WAC 296-24-33001	July 2020	Class B foams	Class B firefighting foams cannot be used or discharged for training purposes, and manufacturers of firefighting personal protective equipment must provide written notification to purchasers if the equipment contains PFAS. Beginning July 1, 2020, manufacturers of class B firefighting foams may no longer manufacture, sell, or distribute for sale PFAS-containing class B firefighting foams except for the following uses: applications where the use of a PFAS-containing firefighting foam is required by federal law, including but not limited to the requirements of 14 CFR 139.317 (such as military and FAA-certified airports). Other exceptions include: Petroleum Terminals (as defined in RCW 82.23A.010), Oil Refineries, Chemical Plants (WAC 296-24-33001)	(Washington State Legislature 2018)
Virginia	House Bill 2762ER	January 2020	PFAS-containing AFFF	Virginia Department of Fire Programs and the Virginia Fire Services Board begin assisting municipal fire departments to transition to F3, where possible. Effective the same date, the bill bans the discharge or use of PFAS-containing AFFF foams for testing or training unless the facility has implemented containment, treatment, and disposal measures to prevent release to the environment.	(State of Virginia, 2019)

3.12.2 Take-Back Programs

Several states have implemented “take-back” programs for AFFF. For example, in May 2018, the Massachusetts Department of Environmental Protection (MA DEP), in partnership with the Massachusetts Department of Fire Services, implemented a take-back program to assist fire departments in the proper disposal of legacy firefighting foams that could impact water resources (MA DEP 2018). MA DEP provided funding to assist local fire departments in identifying these foams in their stockpiles and for MA DEP to dispose of them. Any AFFF manufactured before 2003 is eligible under the take-back program. Vermont also announced a take-back program (VT ANR 2022). Users should contact their state regulatory agency for information on available take-back programs.

3.12.3 Federal Guidance

As of publication, F3s do not meet the performance requirements of the Mil-spec and therefore are not used at federal- and FAA-regulated facilities. A mandate within the FAA Reauthorization Act of 2018 (enacted October 5, 2018) directs the FAA to stop requiring the use of fluorinated foam no later than 3 years from the date of enactment (October 4, 2021), however, per Cert Alert 21-05, no fluorinated Mil-Spec existed as of that date. In January 2023, the FAA released a Cert Alert to all Title 14 CFR Part 139 Certificated Airport Operators and Aircraft Rescue and Firefighting Departments and Mutual Aid Providers (FAA 2023). The alert noted that FAA will accept the airport operator’s use of the new F3 extinguishing agent at certificated Part 139 airports once the agent passes the military performance standards and qualification testing and is added to the Navy’s Qualified Products’ List/Qualified Products’ Database. The alert further noted that currently, the FAA will not require certificated Part 139 airports to transition to the new F3, and airport operators are authorized to continue using AFFF, but should check with their state and local municipalities for any local requirements. The National Defense Authorization Act of fiscal Year 2020 (signed into law Dec 20, 2019) requires the DOD to phase out its use of AFFF at all military installations by Oct. 1, 2024, with limited exceptions, and immediately stop military training exercises with AFFF.

In January 2023, DOD released a new Mil-Spec (MIL-PRF-32725) to replace AFFF with F3s at military installations. The F3 Mil-Spec contains a product qualification step that requires a “non-detect” for PFAS as measured by Draft USEPA Method 1633, and also a specification limitation on PFAS content, prohibiting F3s from containing more than one part per billion PFAS (USDOD 2023).).

3.12.4 International Guidance on AFFF

Internationally, there are many governmental agencies that have developed guidance or operational policy for AFFF. Some examples are briefly presented in Table 3-7. The international guidance and regulations are shaped by the unique regulatory structure and regional history of the areas in which they are implemented. As such, they may not necessarily provide informative insights to readers who are unfamiliar with those specific contexts.

Table 3-7. Representative international AFFF regulatory and guidance activity

Country	Initial Effective Date	What is Regulated?	Specific Requirement	Reference
Canada	January 2018	PFOS, PFOA, long-chain PFCAs	Canada prohibits the manufacture, use, sale, or import of a number of PFAS-containing chemicals and products, such as AFFF, that have these chemicals. Canada allows certain exemptions, including the use of AFFF that contains residual levels of PFOS at a maximum concentration of 10 ppm; the use and import of AFFF contaminated with PFOS in military equipment returning from a foreign military operation; and the import, use, sale, and offer for sale of AFFF that contains PFOA and/or LC-PFCAs used in firefighting.	(ECCC 2017)

Country	Initial Effective Date	What is Regulated?	Specific Requirement	Reference
Canada	2022	PFOS, PFOA, long-chain PFCAs, polybrominated diphenyl ethers (PBDEs), and hexabromocyclododecane (HBCD)	The proposed prohibition would remove or provide time limits for exemptions for PFOS, its salts and precursors, PFOA, its salts and precursors, long chain PFCAs, PBDEs, and HBCD to further restrict the manufacture, use, sale, and import of these substances, and products that contain them. It would also prohibit the manufacture, import, use, sale, and offer for sale of Dechlorane Plus (DP) and decabromodiphenyl ethane (DBDPE), and products that contain them, with exemptions.	(ECCC 2022)
Germany	May 2013	AFFF	The German Federal Environment Agency released a Guide for the Environmentally Responsible Use of Fluorinated Fire-fighting Foams. The guidance discusses what AFFFs are, when it is necessary for use, why it endangers humans and the environment, and the consequences of use.	(German Federal Environment Agency 2013)
Australia	July 2016	Firefighting foam	The Queensland Department of Environment and Heritage Protection issued an Operational Policy on the Environmental Management of Firefighting Foam. The objective of the policy was to define the requirements and expectations for the handling, transport, storage, use, release, waste treatment, disposal, and environmental protection measures of AFFF.	(Australia Government DOD 2007)
Australia	July 2016	Firefighting foam	Australia’s state of Queensland established restrictions on application and procurement of C8-AFFF (eight carbon-fluorine bonds or greater) and designated that C6-AFFF (six carbon-fluorine bonds or less) replacement foams contain less than 10 mg/kg PFOS and less than 50 mg/kg of PFOA, PFOA precursors, and their long-chain homologues.	Queensland DES 2021 (replaced Queensland DES 2016)
Australia	January 2018	Firefighting foam	Australia’s state of South Australia instituted a ban on fluorinated firefighting foams with a grace period of 2 years to complete foam transition.	SA EPA May 2019

Country	Initial Effective Date	What is Regulated?	Specific Requirement	Reference
European Union	July 2020	PFOA, its salts, and related substances	Prohibit the manufacture of PFOA and related substances on their own from 4 July 2020. Products manufactured after 4 July 2020 should not contain PFOA and its salts greater than 25 ppb or sum of PFOA-related substances (e.g., precursors) greater than 1,000 ppb.	European Commission 2017
European Union	December 2021	PFHxA, its salts, and related substances	Proposed a restriction on the manufacture of PFHxA and related substances on their own, as well as in products that contain concentrations equal to or above 25 ppb for the sum of PFHxA and its salts or 1,000 ppb for the sum of PFHxA-related substances.	European Chemicals Agency (ECHA) 2021
European Union	February 2023	C9–C14 PFCAs, their salts, and C9–C14 PFCA-related substances	Prohibit the manufacture of C9–C14 PFCAs and related substances on their own from 23 February 2023. Products manufactured after 25 February 2023 should contain less than 25 ppb for the sum of C9–C14 PFCAs and their salts or less than 260 ppb for the sum of C9–C14 PFCA-related substances.	European Commission 2021

3.13 Foam Research and Development

Current modern AFFF fluorosurfactant alternatives are largely short-chain C6 telomer-based fluorosurfactants. The fluorosurfactants do persist in the environment, and they have the potential to create breakdown products that are also persistent. Although numerous fluorine-free alternatives are already on the market, there is still a need to develop novel firefighting foams that provide the desired firefighting performance while not being harmful to human health and the environment. Research is currently being conducted to further evaluate modern fluorotelomer and fluorine-free alternatives. Research is discussed below.

3.13.1 Research on Current AFFF

Research is being conducted to provide a better understanding of AFFF in the environment and to develop novel technologies to clean up or remove AFFF at contaminated sites. Due to the ability of these legacy AFFF to spread quickly and prevent re-ignition of fuel fires, combined with the fact the USEPA did not require manufacturers to remove their long-chain inventory as part of the 2010/2015 PFOA Stewardship Program, some legacy stockpiles are still being used today (Barclift 2013).

Since 2017, the Strategic Environmental Research and Development Program (SERDP) has been funding research intended to identify and test F3s that meet the performance requirements defined in MIL-PRF-24385. New formulations must be compatible with existing AFFF and supporting equipment. Projects include evaluation of persistence and aquatic toxicity of the alternative materials and will provide human health and environmental impact assessments on the ingredients, formulations, and byproducts being studied. Table 3-8 summarizes the current AFFF alternatives studies supported by SERDP-Environmental Security Technology Certification Program (ESTCP). The user is encouraged to view the results and full reports of these and future projects on the SERDP-ESTCP website (https://serdp-estcp.org/).

Table 3-8. Summary of the AFFF alternatives studies supported by SERDP-ESTCP

Lead Investigator	Objectives	Expected Completion	Project Link
Dr. Joseph Tsang, Naval Air Warfare Center Weapons Division	Proof-of-concept for the development of the next generation of fluorine-free firefighting foam formulations as a replacement for existing aqueous film-forming foam (AFFF). The novel foam systems produced in this research are derived from polysaccharide copolymers and nanoparticles that are sustainable, nontoxic, and water-soluble (or water-dispersible), and will be applied using existing military firefighting equipment.	Aug-18	https://serdp-estcp.org/Program-Areas/Weapons-Systems-and-Platforms/Waste-Reduction-and-Treatment-in-DoD-Operations/WP-2737/WP-2737
Dr. John Payne, National Foam	Improve understanding of the physical and chemical processes that underlie firefighting foams, and how the components of a foam formulation can deliver the properties required for good fire-extinguishing performance while minimizing environmental burdens. Statistical method will be employed to develop a fluorine-free surfactant formulation that meets the performance requirements defined in MIL-F-24385. A life cycle assessment will compare the environmental impact of each foam type and identify routes to improving environmental performance.	Sept-19	https://serdp-estcp.org/Program-Areas/Weapons-Systems-and-Platforms/Waste-Reduction-and-Treatment-in-DoD-Operations/WP-2738/WP-2738
Dr. Ramagopal Ananth, U.S. Naval Research Laboratory	Develop a fluorine-free firefighting surfactant formulation that meets the performance requirements of MIL-F-24385F and is an environmentally friendly drop-in replacement for the current environmentally hazardous AFFF.	Dec-20	https://serdp-estcp.org/Program-Areas/Weapons-Systems-and-Platforms/Waste-Reduction-and-Treatment-in-DoD-Operations/WP-2739/WP-2739
Prabhat Krishnaswamy Engineering Mechanics Corporation of Columbus (Emc2)	WP22-7521. This project’s technical objective is to develop a novel approach for fighting gasoline pool fires based on fire-retardant additive releasing smart beads.	Initiated 2022	https://www.serdp-estcp.org/projects/details/352aa6f8-fae0-4cf6-8080-0fc319700142/wp22-7521-project-overview
Dr. Girish Srinivas TDA Research, Inc.	WP22-7456. TDA Research, Inc.’s objective is to collect baseline data for the PFAS-free foam under MIL-PRF-24385F to inform what specifications could be adjusted to fully evaluate PFAS-free foams for fire suppression and environmental impact.	Initiated 2022	https://www.serdp-estcp.org/projects/details/baa72637-e3c8-40ee-a007-f295311c72ad/wp22-7456-project-overview

Lead Investigator	**Objectives**	**Expected Completion**	**Project Link**
Dr. Tirumalai Sudarshan Materials Modification Inc.	WP22-3456. This project's technical objective is to develop a novel approach for fighting gasoline pool fires based on fire-retardant additive releasing smart beads.	Initiated 2022	https://www.serdp-estcp.org/projects/details/b4cada93-5acf-47ff-ab68-c115a9c6c6ab/wp22-3436-project-overview
Eric Sievert Naval Air Warfare Center Weapons Division	WP21-3461. During this follow-on effort, the capabilities of the top fluorine-free products will be assessed and validated against the test configurations used to assess the capabilities of AFFF 30–40 years ago.	2021	https://www.serdp-estcp.org/projects/details/1bed98f7-dbe6-4bdd-98d2-1f9cfeb5f3d9/wp21-3465-project-overview
Dr. Satya Chauhan Battelle Memorial Institute	WP20-5335. The objective of this project is to provide comparative and unbiased demonstration and validation of mature Fluorine-Free Fire Suppression Alternatives (FF_FSA) against military specifications (MIL-SPEC), specifically MIL-PRF-24385F, as amended, to permit transition to field use as a firefighting agent.	2020	https://www.serdp-estcp.org/projects/details/164cac28-0322-4d7a-8980-80a1146b5afa/wp20-5335-project-overview
Kevin Roth ADA Technologies, Inc.	WP20-5381 Testing of New Fluorine-Free Green Surfactants Mixture to Replace AFFF	4/20/2022 Project Brief	https://serdp-estcp-storage.s3.us-gov-west-1.amazonaws.com/s3fs-public/project_documents/WP20-5381%2BProject%2BOutbrief.pdf?VersionId=5e69zE0HUHJoVs.NrGmWPp1ZiZM1wWjH
Dr. Bridgett Ashley Air Force Civil Engineer Center	WP 20-5381. The goal of a water mist system in an aircraft hangar is to suppress and mitigate fire events and prevent damage to aircraft surfaces that are directly above and/or adjacent to the fuel spill fire.		https://www.serdp-estcp.org/projects/details/cb97638e-8d4e-4892-adce-343575ca862c/wp21-5212-project-overview

Examples of other ongoing research includes:

- European Chemicals Agency, 2020. Assessment of Alternatives to PFAS-Containing Fire-Fighting Foams and the Socio-Economic Impacts of Substitution.
- European Commission, 2020. The Use of PFAS and Fluorine-Free Alternatives in Fire-Fighting Foams.
- The Fiscal Year 2020 National Defense Authorization Act (NDAA), passed in December 2019, included $49M in research funding for AFFF and F3 activities.
- The Fiscal Year 2022 National Defense Authorization Act (NDAA), passed in December 2021, included more than $500 million for PFAS provisions
- NFPA Research Foundation (2022), Fire Fighting Foams: Fire Service Roadmap.

Updated September 2023.

4 Physical and Chemical Properties

The PFAS Team developed a Naming Conventions and Physical and Chemical Properties training video with content related to this section.

This section provides information about available physical and chemical properties of PFAS. Understanding of the physical and chemical properties of PFAS is important for the prediction of their fate and transport in the environment. The available information about physical and chemical properties varies between the different PFAS. Tabulated values are included in the Physical and Chemical Properties Table (Table 4-1) that is provided as a separate Excel file.

Section Number	Topic
4.1	Challenges and Limitations Related to PFAS Physical and Chemical Properties
4.2	Physical Properties
4.3	Chemical Properties

4.1 Challenges and Limitations Related to PFAS Physical and Chemical Properties

Understanding the physical and chemical properties of PFAS is important for the prediction of their fate and transport in the environment. More specifically, reliable values are very important when attempting to explain the environmental behavior of PFAS through mathematical fate and transport modeling, where small variations in values can have large implications on predictions (see Section 10.4 on data analysis and interpretation, which includes a discussion of fate and transport modeling). There is large variation in both the quantity and robustness of published data (a lot is known about some PFAS, but almost nothing about others) on chemical and physical properties of PFAS. Reliable physical and chemical properties of PFAS are scarce (for example, vapor pressure and Henry’s Law constants), and some of the available values are estimated using predictive mathematical techniques, which predict properties of compounds from knowledge of their chemical structure. These are collectively referred to as quantitative structure-activity relationship (QSAR) models. Predicted, as opposed to directly measured, values are accompanied by additional uncertainty that may be significant in certain fate and transport modeling scenarios. In addition, many of the available properties are based on the acid form of the PFAAs, which is not present in the environment except at low pH. These uncertainties can result in wide ranges of reported values and thus limit confidence in the precision of current fate and transport models. The Physical and Chemical Properties Table (Table 4-1 provided as a separate Excel file) summarizes some of the physical and chemical properties that are available for PFAS. The object of this table is to serve as a starting point for the research and selection of relevant properties by the practitioner. Selection of appropriate physical and chemical parameters for a specific use is beyond the scope of this document.

4.2 Physical Properties

This section briefly describes some standard physical properties of PFAS. Additional references for more information are provided. In addition, the Physical and Chemical Properties Table (Table 4-1 provided as a separate Excel file) summarizes some of the physical and chemical properties that have been published for PFAS and are discussed in this section.

4.2.1 Physical State/Appearance

Most PFAS are solids, often crystalline or powdery in form, at room temperature; however, shorter chained compounds (the acid forms of PFCA and PFSA, FTS and FTOH with a 4- to 6-carbon tail) tend to take liquid form at room temperature (melting point is addressed in Section 4.2.3).

4.2.2 Density

Density (ρ) is the mass per unit volume of a substance. For an individual PFAS compound (or mixture of PFAS) that exists as a liquid at ambient temperatures, density can influence its behavior in the environment.

If the density of the liquid PFAS is greater than that of water, the liquid PFAS has the potential to migrate downward through the water column in groundwater or surface water as a dense nonaqueous phase liquid (DNAPL); see ITRC (2003) for discussion on density and solubility impacts on DNAPL behavior. For example, 4:2 FTOH, which is a liquid at 20°C and has a density and aqueous solubility of 1.59 g/cm^3 and 974 mg/L (Table 4-1), respectively, would be predicted to behave similarly to carbon tetrachloride (with a density of 1.59 g/cm^3 and a solubility of 800 mg/L) if released into the environment as a pure product (also referred to as a neat liquid). However, if 4:2 FTOH dissolved in water, the change in density of the solution relative to water is unlikely to result in a separate layer. Floating separate-phase liquid layers have been observed on the surface of aqueous PFOA and PFOS solutions at high concentrations (Costanza et al. 2019). However, the formation of these layers appears to be driven by the tendency of PFAAs to accumulate and aggregate at air-water interfaces, and not by density. See Sections 4.2.8, 5.2.2.2, and 5.2.4.1 for additional information on the behavior of PFAS at air-water interfaces and in aqueous solutions.

4.2.3 Melting/Boiling Points

Melting and boiling point information refers to the temperature of phase transitions of pure compounds. These properties determine whether a specific pure PFAS compound will exist as a liquid, solid, or gas under typical environmental temperatures. These data can vary among references. Predicted melting and boiling point values are available for most PFAS, but empirically derived values are not available for many compounds. Predicted values are generally useful in understanding the various physical states of PFAS; however, the accuracy of these results is still unknown and warrants further investigation. Available data indicate that melting and boiling points of PFAS will tend to increase as the fluorinated chain increases in length. For example, the melting point of PFBA is -17.5°C while the melting point of perfluorotetradecanoic acid (PFTeDA) is 130–135°C. See Table 4-1 for a list of melting and boiling points.

4.2.4 Solubility

Solubility (S) refers to the ability of a given substance, the solute, to dissolve in a solvent. It is measured in terms of the maximum amount of solute dissolved in a solvent at a specified temperature and pressure. Typical units are milligrams per liter (mg/L) or moles per liter (mol/L). Currently, experimentally measured data for the solubility of PFAS in water are available for many of the well-studied compounds, but values are still needed for less studied compounds. This limited availability of experimental data should be considered when relying on PFAS solubility data. Most cited values are based on predicted or modeled values and the input values to these calculations may themselves be estimates. Further, because some PFAS can form different types of supramolecular assemblies, as discussed in Section 4.2.7, the reported water solubilities may include microdispersions of micelles or hemi-micelles in addition to truly solubilized molecules.

Values of solubility for the acid forms of PFAAs and other PFAS are summarized in Table 4-1. Reported values for solubility of individual PFAS analytes may vary depending upon the method used to determine solubility, the form of the analyte (that is, acid or salt), pH, salinity, and whether the value is empirical or obtained through modeling. For example, laboratory studies of water solubilities for PFOS indicate that solubility decreases when the water salt content increases (3M Company 2000). Other factors may affect the reported value of solubility as well.

4.2.5 Vapor Pressures (V_p)

Vapor pressure is an indication of the tendency of a substance to partition into the gas phase. Vapor pressure is a measure of volatility in that the higher the vapor pressure of a compound, the more volatile it is. Compounds with higher vapor pressures, because they are in the gaseous phase or sorbed to aerosols in the atmosphere, have a higher potential for long-range transport. Compounds with lower vapor pressures, which are more likely to remain in solid or liquid form, are transported only via soil or surface/groundwater (Barton, Botelho, and Kaiser 2008), unless they are dissolved into airborne water droplets or sorbed on airborne particulates, as discussed in Sections 5.3.2 and 6.1.

Values for vapor pressure of PFAS are summarized in Table 4-1. Although there are multiple values for PFCAs, FASEs, and FTOHs, very little data exist for measured vapor pressure values for PFSAs, fluorotelomer acids, and perfluoroalkyl ether compounds, and much of the data are extrapolated or modeled. Caution must be taken when using the vapor pressures for PFAAs listed in Table 4-1 with respect to the acid or anion form of the compound, which may have very different vapor pressures. Efforts were made to report the values for the acidic form in Table 4-1, but references are not always clear. These values also should not be used for their corresponding salt form for the same reason (for example, the vapor pressure of ammonium perfluorooctanoate has been measured experimentally to be three orders of magnitude lower than the vapor pressure of perfluorooctanoic acid at 25°C (Barton, Botelho, and Kaiser 2009)).

4.2.6 Henry's Law Constant (K_h)

The Henry's law constant (K_h), as well as the air-water partition coefficient (K_{aw}), indicate the relative concentrations of a compound between an aqueous solution and gas phase at equilibrium (air-water distribution ratio) and provide an indication of the propensity of a chemical to remain dissolved in water versus volatilizing into the gas phase. A chemical with lower solubility and higher volatility will have a higher Henry's law constant than a chemical with higher solubility and lower volatility.

For most organic compounds of moderate to low solubility, K_h can be approximated by:

$$K_h = (V_p)(M)/S$$

where K_h is the Henry's law constant, V_p is vapor pressure, M is molecular weight, and S is solubility. This constant can be expressed in a variety of units or as the inverse (water-air distribution ratio); thus, the units of expression should always be confirmed prior to use of this constant. K_h also displays nonlinear temperature-dependence and is typically reported at 25°C, which is higher than most ambient environmental conditions.

Experimental and modeled Henry's law constants are available for many PFAS in several families, including FTOHs (for example, Wu and Chang (2011) and Xie et al. (2013)), PFSAs, PFCAs, FTCAs, FTSAs, FASEs, and FASAAs (for example, Kwan (2001) and Zhang et al. (2010)). For PFAS that can dissociate into anions or cations, as discussed in Section 4.3.2, the Henry's law constant is pH-dependent and reported constants may not be applicable depending on the pH conditions within the solution (for example, Rayne and Forest (2009) and Johansson et al. (2017)). In a study of airborne PFOA release in industrial settings, monitoring above sumps found concentrations 40 times greater when the pH was 1.8 than at neutral pH, and PFOA release from aqueous solution was found to be several times greater at pH 4 than at pH 7 (Kaiser et al. 2010). Henry's law constant values, converted between a variety of units, are presented in Table 4-1. Corresponding K_{aw} values and, where available, the temperature and pH at which the value is relevant, are also presented.

4.2.7 Critical Micelle Concentration

Given the difference in behavior between the "head" and "tail," traditional surfactants (surfactants that contain a hydrocarbon chain), when in water, tend to aggregate into micelles (form a sphere with the hydrophobic portion of the molecules on the inside) when present above a certain concentration. Surfactants can also form other supramolecular assemblies, such as hemi-micelles or mixed micelles (micelles composed of a mixture of surfactant-type molecules), either independently in solution or at boundaries occurring between phases (Krafft and Riess 2015).

Early studies of PFAAs concluded that they behaved like traditional surfactants and aggregated in both micelles and mixed micelles (Pedone et al. 1997; Downer et al. 1999). The theoretical threshold concentrations for aggregation, generally referred to as critical micelle concentrations (CMCs), for PFAS are presented in Table 4-1. However, there remain some observed properties of PFAS that do not fit the traditional understanding of micelle formation. For example, it appears that some reported CMC concentrations are above the known corresponding solubilities of that compound. For example, López-Fontán, Sarmiento, and Schulz (2005) reported a PFOA CMC of more than 12,000 mg/L when the reported solubilities of PFOA are generally less than 10,000 mg/L (see Table 4-1). Several reported CMC concentrations for PFOS are also above the reported solubility values (Yu et al. 2009; Sørli et al. 2020; Bhhatarai and Gramatica 2011). In addition, Costanza et al. (2019) reported a separate-phase liquid at the surface of high-concentration solutions of PFOS and PFOA. These anomalous breaks with traditional micelle formation behavior have yet to be fully explained in the literature. Some researchers have also postulated that the nature of PFAA supramolecular aggregations is much more complicated in environmental settings than formation of micelles at concentrations exceeding the CMC value, which is derived from single compound systems. Some have hypothesized that PFAA supramolecular aggregations may occur at concentrations much lower than the CMC in groundwater, due to interactions with particles and/or co-contaminants, formation of hemi-micelles, or spatially variable concentrations within soil matrices (Johnson et al. 2007; Yu et al. 2009). Other researchers have been studying the variable nature of PFAS micelles in the presence of solvents (Dong et al. 2021). These hypothesized supramolecular aggregations, coupled with the interrelationship of adsorption to interfaces such as the air-water interface, present an extremely complex set of interactions that may be occurring in the environment. It is evident that there is much more research to be done on this topic, which can aid our understanding in what may be a key PFAA characteristic that influences fate and transport in the environment. This topic is further discussed in Section 5.2.

4.2.8 Partitioning to Fluid-Fluid Interfaces

The amphiphilic structure of PFAAs (hydrophobic tail with hydrophilic head) implies that they behave like traditional surfactants, accumulating to the fluid-fluid interfaces (for example, air-water or NAPL-water) by orienting themselves along the air-water boundary so that their hydrophobic tails are in the air while their hydrophilic head groups are in the water (Krafft and Riess 2015; Figure 4-1). Although there has been a good deal of research done that confirms surface aggregation, the actual structure of the molecular assemblies has not yet been elucidated. Work done by Hasegawa et al. (2017), however, has provided some theories that the aggregational shape of PFAS may be more complex than that of traditional surfactants and depend on the length of the fluorinated tail.

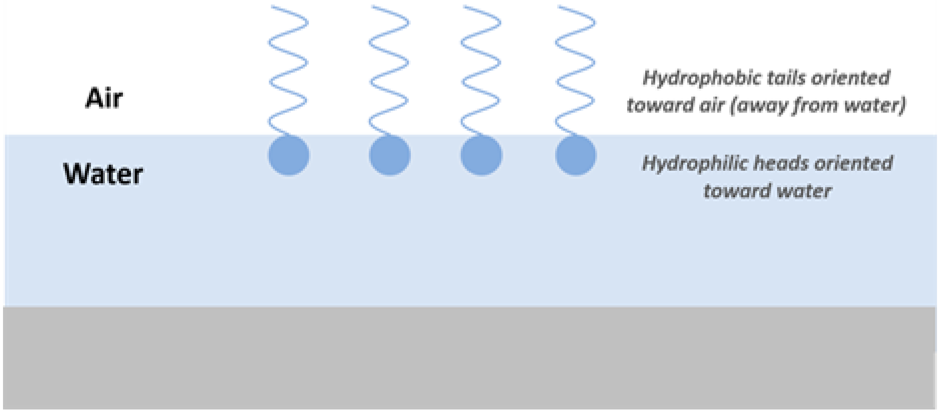


Figure 4-1. Example of expected orientation and accumulation of PFAS at air-water interface.

Source: D. Adamson, GSI. Used with permission.

Because of the low polarizability of the C-F bond relative to the C-H bond, PFAAs have a stronger affinity for interfaces than that of traditional hydrocarbon surfactants (Brusseau 2018). These strong surface-active properties and propensity toward self-assembly into films are what makes PFAAs extremely effective and widely used in a variety of applications such as water/grease repellent packaging and AFFF.

Studies have shown that PFAAs are enriched at the air-water interface up to eight times that of the bulk water concentration, with enrichment factors increasing with alkyl chain length (Psillakis et al. 2009; Costanza et al. 2019; Silva et al. 2019; Schaefer et al. 2019). A similar process is thought to occur for PFAAs at NAPL-water interfaces (Brusseau 2018; Silva et al. 2019; Brusseau 2020), however, the magnitude of accumulation at the NAPL-water interface appears to be far less than at the air-water interface at environmentally relevant concentrations. Recently, Costanza, Abriola, and Pennell (2020) reported that concentrations of PFOA, PFOS, and FOSA at the air-water interface were from 2 to 16 times greater than at the NAPL-water interface when the PFAS water concentrations were below 100 mg/L. This study also estimated that, in an unsaturated soil system with a dissolved water concentration below 1 mg/L, up to 87% of the PFOS mass accumulates at the air-water interface, while less than 4% of the mass occurs at the dodecane-water interface.

The degree of affinity that PFAAs exhibit for interfaces is related to the change in surface tension that occurs between the fluids when the compound is introduced to the system. Generally, the surface tension and affinity for the interface both go down as the amount of PFAA increases in the system, although the relationship is not linear. This means that the relationship is influenced by other factors that also effect the surface tension at interfaces (for example, the ionic strength and pH of the solution). For example, Constanza et al. (2019) found that the reduction in surface tension was more pronounced as the total dissolved solids increased (for TDS = 40, 400, and 1700 mg/L), which corresponded to greater accumulation of PFOA and PFOS at the air-water interface.

The adsorption coefficient for the fluid-fluid interfacial layer, termed the K_i (also called the K_{ai} or K_{ia} for the air-water interface or the K_{ni} for the air-NAPL interface) is one metric for the affinity of a compound for fluid-fluid interfaces. However, calculation of the K_i is highly dependent on which assumed sorption model (Freundlich vs. Langmuir) is used, and values can vary by orders of magnitude at low concentrations (Schaefer et al. 2019). Because of this, it can be more useful to measure the affinity using the metric of surface excess (Γ, units of mg/m^2 or mol/m^2), which is the area-related concentration at the interface as compared to the bulk phase (Costanza, Abriola, and Pennell 2020). Because of the complicated nature of interfacial adsorption, adsorption coefficient values are not reported in Table 4-1.

4.2.9 Octanol/Water Partition Coefficient (K_{ow})

The K_{ow} is defined as “the ratio of a chemical’s concentration in the octanol phase to its concentration in the aqueous phase of a two-phase system” (USEPA 2015). The Kow is a useful descriptor of the tendency of a compound to associate with hydrophobic or hydrophilic substances. Direct measurement of the K_{ow} of PFAAs has proven difficult because they tend to aggregate at the interface between octanol and water (Kim et al. 2015), although some researchers have employed nontraditional methods with some success (Jing, Rodgers, and Amemiya 2009). Alternatively, K_{ow} can be estimated using quantitative tools that predict physical and chemical properties. The K_{ow} values that are typically tabulated for the PFCAs and PFSAs are for the acid form and are therefore not directly relevant to the anionic forms of PFCAs and PFSAs that exist within the typical range of environmental pH, although the K_{ow} for the anionic form can potentially be estimated from the K_{ow} for the neutral species (Escher et al. 2020).

K_{ow} values are often used as surrogates for other properties, such as estimating K_{oc}, the soil organic carbon/water partition coefficient; bioaccumulation; uptake in biological systems; and ecotoxicity. However, in the case of PFAS, the use of their K_{ow} values as surrogates is generally not appropriate because PFAS do not behave like other well-researched nonionic polar chemicals. For example, the use of K_{ow} as a surrogate for bioconcentration assumes partitioning to lipids in fatty tissues, but ionic PFAS such as PFOA and PFOS generally bind to proteins. See Section 5.5 for further discussion about PFAS uptake into aquatic organisms. For these reasons, K_{ow} values are not presented in Table 4-1.

4.2.10 Organic Carbon/Water Partition Coefficient (K_{oc})

K_{oc} is a metric commonly used to quantify the potential of a given dissolved compound to associate with, or sorb to, organic matter occurring in soil. Although short- and long-chain PFAAs both exhibit high potential mobility in water, long-chain PFAS are more likely to partition to sediment than short-chain PFAAs (Dalahmeh et al. 2018). Relative to commonly researched PFAS like PFOA and PFOS, studies have suggested K_{oc} can be appropriately defined as a distribution coefficient (K_d) normalized to organic carbon content, thus implying K_{oc} specifically represents the singular process of hydrophobic interaction (Milinovic et al. 2015). Broader reviews highlight the complexity and variability of processes that may contribute to the sorption of PFAS and significant differences between laboratory- and field-scale results (Li, Oliver, and Kookana 2018). These reviews, which cite the influence of pH, ionic composition, and other soil properties on sorption, suggest that simple hydrophobic interaction-based relationships may be unreliable for predicting partitioning for PFAS (see Section 5.2 for more discussion on partitioning). As such, the current state-of-science supports K_{oc} being reported in relatively broad ranges on a compound-specific basis. The K_{oc} values included in Table 4-1, while not an exhaustive list, are an indicator of the number of values currently available for PFAS. Discussion of the use of K_{oc}, including site-specific K_{oc}, in the prediction of PFAS transport in remedial scenarios is included in Section 10.4.2.

4.2.11 Partitioning to Biota

The extent of accumulation of PFAAs in organisms is controlled by several mechanisms, including uptake from food and from water, depuration, growth dilution, and biotransformation. These processes are described in Section 5. Within organisms, PFAA accumulation differs among tissues, depending on transport factors (for example, the ability to cross the blood-brain barrier, as discussed in Dassuncao et al. (2019) or active cellular transport (as discussed in Section 17.2.3) as well as partitioning. Partitioning is the subject of this section.

Similar to solids partitioning in the environment, the surfactant structure of PFAAs determines the types of interactions that occur within biota. Nonionic hydrophobic chemicals are known to partition into lipids within body compartments. PFAAs are amphiphilic, however, and thus are likely to interact with other organic molecules with both polar and nonpolar regions within living organisms. Many studies have found significantly different PFAA concentrations between body compartments, with the most accumulation occurring in the blood plasma, liver, and kidneys of many organisms (Labadie and Chevreuil 2011; Goeritz et al. 2013; Murakami et al. 2011). This marked difference in PFAA concentrations between bodily compartments has prompted some researchers to deem PFAAs "proteinophilic" to contrast with the description of other well-researched neutral hydrophobic environmental pollutants as "lipophilic" (Kelly et al. 2009; Labadie and Chevreuil 2011). Indeed, these differences in accumulation are likely, at least in part, due to interaction with/partitioning to proteins, which have binding pockets with varying charges that can interact with amphiphilic molecules like PFAAs. However, because the size, shape, and charge of binding pockets vary widely between proteins, there is an evident difference in PFAA binding between types of protein. Multiple studies have found strong interaction of PFAAs to serum albumin, fatty acid–binding proteins, and organic anion transporters (Chen and Guo 2009; Zhang, Ren, and Guo 2013). The magnitude of protein binding affinity differs with the type of PFAAs; Zhang, Ren, and Guo (2013) found that PFAA chain length and functional group determined the amount of binding affinity, but the relationship between binding and chain length was not linear. They also found that FTOHs (neutral charge molecules) did not bind to fatty acid–binding proteins, indicating that the charge of the functional group plays a large part in the protein interaction.

In addition to proteins, PFAAs likely interact with phospholipids (the basic building block of cell membranes). Dassuncao et al. (2019) found a positive correlation between PFAA and phospholipid content in several body compartments of pilot whales. It has been suggested that the interactions occur because of the amphiphilic nature of both phospholipids and PFAAs, which have the potential for binding at both their polar and nonpolar regions (Armitage, Arnot, and Wania, 2012). However, researchers have not found evidence that these interactions are the main determinant of tissue binding. Dassuncao et al. (2019) noted variability in the correlations between phospholipid content and tissue concentrations and concluded that the variability was likely due to the combined effect of protein and phospholipid partitioning.

For nonionic hydrophobic compounds, differences in lipid content can explain some of the variation in chemical concentration among organisms; under some conditions, individuals with higher lipid content have higher body burdens. In general, protein content differs to a much smaller extent among organisms than does lipid content, suggesting that differences in protein partitioning among individuals do not contribute strongly to differences in body burden among individuals. However, the sources of interindividual variation in PFAA body burdens is not well-understood and there is no current framework to incorporate our understanding of PFAS partitioning (for proteins and phospholipids, as well as lipids, which may still have a role) into reliable models for the prediction of bioaccumulation, biotransfer, or biomagnification.

4.3 Chemical Properties

This section briefly describes some standard chemical properties of PFAS. Additional references are provided for more information. In addition, the Physical and Chemical Properties Table (Table 4-1 provided as a separate Excel file) summarizes some of the physical and chemical properties that are available for PFAS.

4.3.1 Carbon-Fluorine (C-F) Bond Properties

The properties of PFAS are principally due to the unique properties of the carbon-fluorine bond. Some key chemical properties of this bond and the characteristics they impart to PFAS are provided in Table 4-2.

Table 4-2. Fluorine characteristics

Fluorine Characteristic	Description	Effect	Resulting Property of PFAS
High electronegativity	Tendency to attract shared electrons in a bond	Strong C-F bond	Thermal stability
			Chemical stability (low reactivity)
		Polar bond with partial negative charge toward F	Strong acidity (low pKa)[1]

Fluorine Characteristic	Description	Effect	Resulting Property of PFAS
Low polarizability	Electron cloud density not easily impacted by the electric fields of other molecules	Weak intermolecular interactions	Hydrophobic and lipophobic surfactant properties[2]
		Low surface energy	
Small size[3]	Atomic radius of covalently bonded fluorine is 0.72 Å	Shields carbon	Chemical stability (low reactivity)

[1] When paired with an acid functional group such as a carboxylic or sulfonic acid

[2] When paired with a functional group that is hydrophilic (for example, a carboxylate)

[3] Smallest of the halogen atoms
Å = angstrom

Properties such as the high electronegativity and small size of fluorine lead to a strong C-F bond, the strongest covalent bond in organic chemistry (Kissa 2001). The low polarizability of fluorine further leads to weak intermolecular interactions, such as Van der Waals interactions and hydrogen bonding (Kissa 2001). These unique properties of fluorine give many PFAS their mutually hydro- and lipophobic (stain-resistant) and surfactant properties and make them thermally and chemically stable. But not all of these characteristics (for example, surface activity) are universal to all PFAS.

4.3.2 Functional Group Properties

PFAS functional groups include carboxylates, sulfonates, sulfates, phosphates, amines, and others, as introduced in Section 2.2.2. These functional groups, including dissociated and undissociated forms, govern many fate and transport properties of PFAS. The ionic state of a compound determines its electrical charge and its physical and chemical properties, which in turn control its fate and transport in the environment. For example, the state (anionic or undissociated acid) of a given PFAS may alter aspects such as volatility and bioaccumulative potential. As further described below, due to their low acid dissociation constants (K_a), PFAAs are found in the environment in the anionic (negatively charged) state, except in very rare situations (for example, pH <3).

Functional groups of some PFAS (ionic PFAS) can dissociate into anions or cations in aqueous solution under appropriate pH conditions. For example, as discussed in Section 2.2.2, PFOA dissociates into the perfluorooctanoate anion and the hydrogen ion when dissolved in water over a wide range of pH conditions. The ion associated with the fluoroalkyl portion of ionic PFAS can be a negatively charged anion, a positively charged cation, or a zwitterion. Therefore, PFAS can be divided into four classifications based on functional groups (examples of the structures of many ionic PFAS can be found in Barzen-Hanson et al. (2017):

- anionic–contains one or more acidic functional groups such as carboxylic acids, sulfonic acids, sulfates, and phosphates, and can release a hydrogen ion, thereby forming an anion (see Figure 2-8 for PFBA dissociation)
- cationic–contains one or more basic functional groups such as amines, which can gain a hydrogen ion and form a cation, or have a permanent charge as in the case of a quaternary ammonium group
- zwitterionic–contains two or more functional groups, at least one of which can form an anion and one of which can form a cation
- nonionic–does not dissociate into ions; for example, alcohols.

Based on the behavior of other cationic and anionic surfactants, cationic PFAS are expected to have different environmental transport characteristics than anionic PFAS (Place and Field 2012). For example, sorption of organic anions such as PFAA anions is typically suppressed at higher pH due to electrostatic repulsion with the increasingly negative charge from deprotonated oxides and other functional groups present on the soil surface (Lee and Mabury 2017). Cations can be expected to sorb strongly to soils, which often possess a net negative charge over a range of environmentally relevant pHs. For example, cationic fluorotelomer-based PFAS in an AFFF product have been found to sorb strongly to soils and sediments (Barzen-Hanson et al. 2017). Zwitterionic PFAS can be expected to sorb to soils and sediment more strongly than anionic PFAS, but less strongly than cationic PFAS, owing to the mixed charges on the functional groups. The transport characteristics of specific PFAS are also highly dependent on matrix interactions, and detailed site-specific information is necessary to accurately predict PFAS transport (Guelfo and Higgins 2013). See Section 5.2.3 for further discussion of partitioning onto solid matrices.

For acids such as PFAAs, the acid dissociation constant K_a is the equilibrium constant for the dissociation of the acid in aqueous solution into the anion and hydrogen ion, and at dilute to moderate concentrations, is defined by the equation:

$$K_a = [anion^-]*[H^+]/[acid]$$

where [acid] is the concentration of the undissociated acid form, $[anion^-]$ is the concentration of the anion, and $[H^+]$ is the concentration of the hydrogen ion at equilibrium.

The dissociation constant is also commonly expressed as its negative logarithm, pK_a, where:

$$pK_a = -\log_{10}(K_a)$$

Higher pKa values indicate that an acid will dissociate less in water at a given pH than will an acid with a lower pKa. When the pH of a solution equals the pKa for a particular constituent, then one half of the constituent molecules will exist as the undissociated acid and one half will exist as the dissociated anion. PFAS with pKa values of 4 or less will exist in aqueous solutions at neutral pH (7) almost entirely as the dissociated acid (see Figure 4-2 for a representation of reported pKa values for PFOA in relation to environmental pHs). Because the undissociated acid and anionic forms of PFAAs may have very different physical and chemical properties, it is essential to distinguish between the undissociated acid form and the anionic form to select the appropriate physical and chemical parameters for fate and transport evaluations.

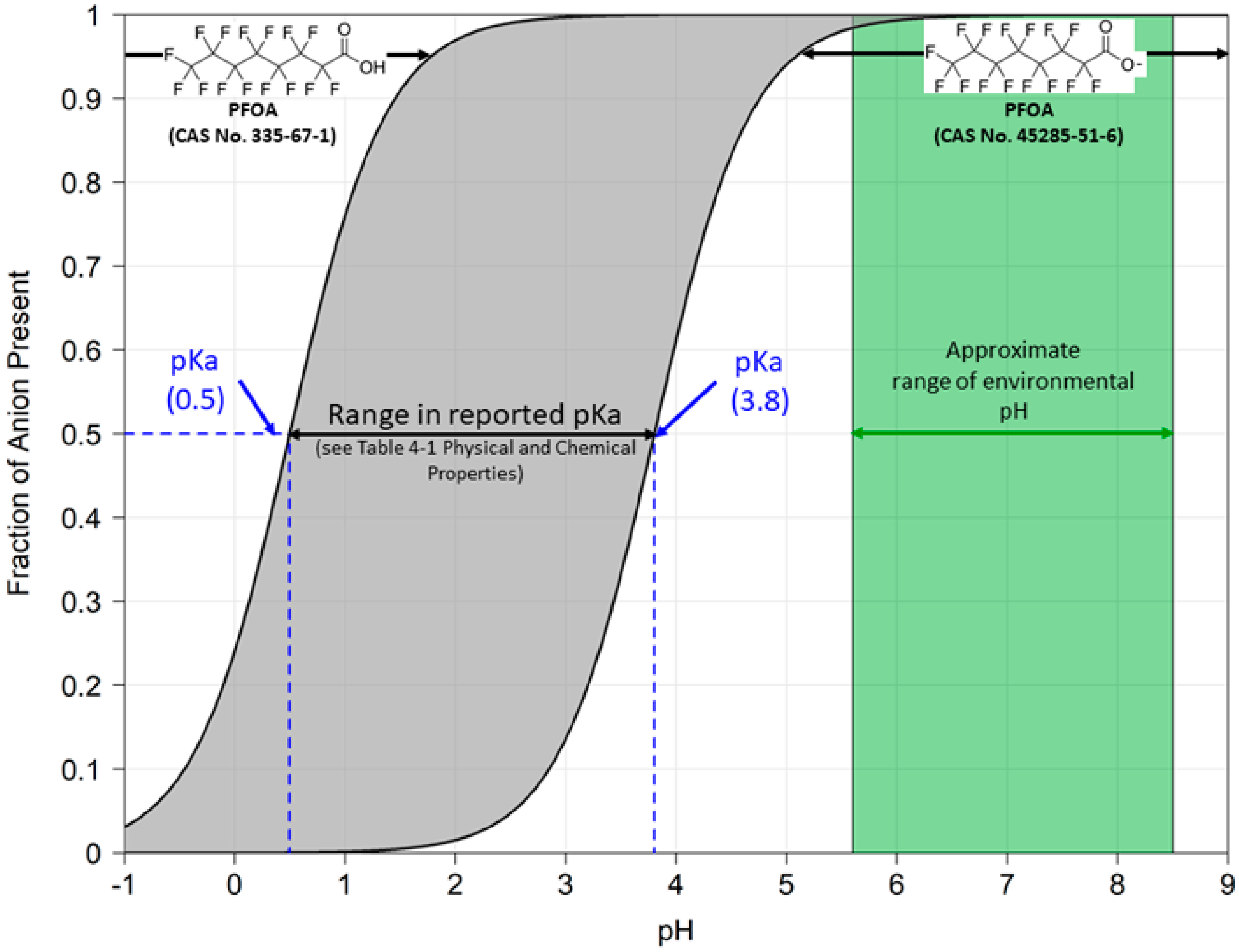


Figure 4-2. Titration curve for PFOA—relation of pKa to environmental pH.

Source: E. DiFilippo, S.S. Papadopulos & Associates, Inc. Used with permission.

Table 4-1 presents pK_a values for PFAS. Limited model-predicted and experimental values are available for most PFAAs.

4.3.3 Thermal Stability

Thermal stability, the degree to which a chemical remains intact under thermal stress, is an important property to predict how long a chemical will persist in the environment. PFAAs, such as PFOA and PFOS, are extremely stable, thermally and chemically, and resist degradation and oxidation. Thermal stability of PFAAs is primarily attributable to the strength of the C-F bond in the fluoroalkyl tail (Kissa 2001), but the relative stability is also determined by the specific functional group that is attached to the fluoroalkyl tail. PFCAs and PFSAs are the most thermally stable fluorinated surfactants. The temperatures at which PFAAs decompose and complete mineralization occurs is an area of active research (see Section 12.4). Reports on temperature needed to destroy PFAS vary, but it seems that to destroy PFAS in soil, temperatures upwards of 1,000°C may be required (Colgan et al. 2018; Winchell et al. 2021). It was previously reported that limited PFOS, PFOA, and PFHxA mineralization (less than or equal to 72%) may occur at temperatures of 700°C (Watanabe et al. 2018). In this same study, mineralization reportedly increased to 90% in the presence of granular activated carbon and sodium hydroxide. The thermal stability is lower for the salts of PFAA compounds and depends on which cation is the counterion. For example, the 20% decomposition temperature of sodium perfluorooctanoate is 298°C, but it is 341°C for lithium perfluorooctanoate (Kissa 2001). Additionally, salts of PFSAs are more thermally stable than the corresponding salts of PFCAs (Kissa 2001).

4.3.4 Chemical Stability

Like thermal stability, knowledge of the chemical stability of a molecule helps predict its persistence in the environment. PFCAs and PFSAs have been shown to be persistent in the environment. PFCAs are resistant to oxidation under environmental conditions; however, transformation has been demonstrated in the presence of oxidants under extreme pressure. In contrast, transformation of precursors can be associated with substantial changes in the physicochemical properties of those compounds (CONCAWE 2016).

In the perfluorinated tail of the alkyl acids, the strength of the C-F bond, shielding of carbon by fluorine, and inductive effects (caused by fluorine electronegativity) also lead to chemical stability. For example, electron-rich chemical species called nucleophiles normally would be attracted to the partial positive charge of carbon. If these nucleophiles could get close enough to the carbon to bond, the subsequent reaction could replace a fluorine with the nucleophile and potentially make the molecule vulnerable to degradation. But the relatively large size of the fluorine atoms surrounding the carbon (when compared to hydrogen) prevents this from happening (Schwarzenbach, Gschwend, and Imboden 2003). This is why processes such as hydrolysis, which involve eliminating one or more fluorines, are ineffective at degrading the perfluorinated tails of PFAAs. Similarly, many PFAAs are resistant to degradation by oxidative processes that rely on a loss of electrons (Kissa 2001). PFAAs are also resistant to reductive processes, which involve gaining electrons. Despite having a high affinity for electrons, fluorine does not have vacant orbitals favorable for accepting additional electrons (Park et al. 2009). In contrast to the stability of perfluorinated tails, polar regions of PFAS (the functional groups), as well as polyfluorinated groups, can be vulnerable to a range of chemical transformations. See Section 5.4 for further discussion of abiotic and biotic transformations.

Updated September 2023.

5 Environmental Fate and Transport Processes

The PFAS Team developed a Fate and Transport training video with content related to this section.

This section provides current information about PFAS fate and transport in the environment. Understanding relevant fate and transport processes for PFAS is critical in evaluating the potential risk from a release, where to look for PFAS following a release, and what treatment alternatives may be effective. The available information about fate and transport processes varies between the different PFAS. PFAS fate and transport is a rapidly evolving field of science.

Section Number	Topic
5.1	Fate and Transport Introduction
5.2	Phase Partitioning
5.3	Media-Specific Migration Processes
5.4	Transformations
5.5	PFAS Uptake into Aquatic Organisms
5.6	PFAS Uptake into Plants

5.1 Fate and Transport Introduction

5.1.1 Overview of PFAS Fate and Transport

PFAS fate and transport describes the behavior of these compounds following their release to the environment. This includes the physical, chemical, and biological processes that influence distribution of PFAS in various media, as well as the extent of migration within and between media (for example, plume development, groundwater discharge to surface water). Given the wide variety of PFAS, it is not surprising that they collectively exhibit a wide range of different physical and chemical characteristics that can affect their behavior in the environment. This adds to the complexity of fate and transport assessments and highlights the risk in making broad assumptions based on the behavior of a few well-studied PFAS.

Understanding relevant fate and transport processes for PFAS is critical in answering several key questions:

- ***What are the transport mechanisms for PFAS in the environment?*** PFAS fate and transport characteristics can assist understanding of the mechanisms through which PFAS discharge and migration may occur (for example, atmospheric/vapor transport, surface water runoff, infiltration into the subsurface, vadose zone sorption/leaching, groundwater migration).
- ***What is the potential risk from a PFAS release?*** An understanding of fate and transport processes provides the basis for defensible predictions about occurrence, migration, persistence, and potential for exposure.
- ***Where do I need to look for PFAS following a release?*** Knowledge of PFAS fate and transport characteristics strongly informs site characterization by providing insight on where efforts should be focused and developing an appropriate conceptual site model (CSM).
- ***How can I treat PFAS?*** Establishing how these compounds behave in the environment is important in developing and/or selecting PFAS treatment strategies.

5.1.2 Factors Affecting PFAS Fate and Transport

Factors that influence PFAS fate and transport can be broadly divided into two categories:

- ***PFAS characteristics:*** Critical factors include the chain length, the ionic state of the compound (for example, the charge(s) carried by the molecule at a typical environmental pH), the type of functional group(s), and the extent of fluorination (for example, perfluorinated versus polyfluorinated compounds). These properties strongly influence the type and extent of PFAS partitioning and transformation that can be expected to occur. A description of these physical-chemical properties is provided in Section 4.

- ***Site characteristics:*** Site characteristics generally define the nature of the source but also have an effect on PFAS-media interactions. Potentially relevant characteristics include soil type (including properties such as permeability, surface charge, organic carbon content, exchange capacity, mineralogy, water content), depth to groundwater, aquifer characteristics (for example, geology, presence of confining layers), oxidation-reduction conditions, precipitation/infiltration rates, groundwater velocities/flow directions, groundwater/surface water interactions, surface water flow rates, prevailing atmospheric conditions, and the presence of co-contaminants.

The characteristics of sites with releases of PFAS often share many similarities with sites having releases of other contaminants, although there are some source scenarios that are relatively unique to PFAS (see Section 2.6 for description of source scenarios). In addition, relevant transport pathways for PFAS can be similar to those for other contaminants. For example, transport of PFAS in groundwater as the result of advection is a potential concern at many sites where PFAS-containing products have been released. Although many PFAS share similar characteristics, such as resistance to transformation, those same PFAS may have widely varying physical-chemical properties, such as those associated with partitioning. As a result, PFAS fate and transport in the environment can be quite different from other contaminants. Therefore, this section focuses on mechanisms where PFAS behavior is different from other contaminants.

5.1.3 Section Organization

This section includes a detailed description of several processes that are particularly relevant for PFAS fate and transport and are illustrated in Figure 5-1.

- ***Partitioning:*** Both hydrophobic partitioning to organic carbon and electrostatic interactions between charged surfaces and PFAS are discussed, along with the tendency of PFAS to aggregate at air-water interfaces. These processes can affect migration in the environment by promoting retention within sediments and unsaturated soils, as well as retardation within groundwater. Varying degrees of retention on solids can contribute to differential transport where certain PFAS (for example, short-chain, anionic) are more rapidly transported than others.

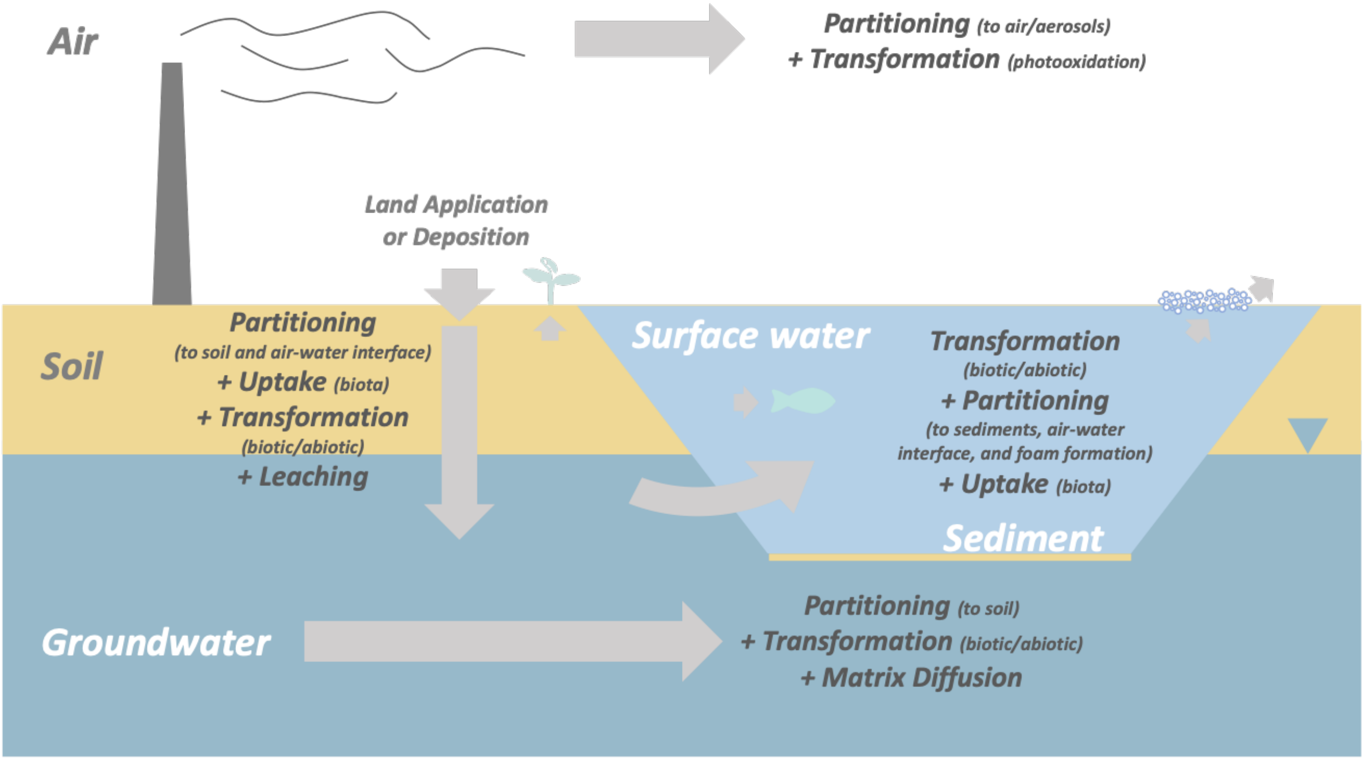


Figure 5-1. Fate and transport processes relevant for PFAS.
Source: D. Adamson, GSI. Used with permission.

- ***Media-specific processes:*** The potential impact of processes such as diffusion into low-permeability matrices, atmospheric transport, and leaching from soil to groundwater are described. Unlike the broader processes of partitioning and transformation, most of these processes are unique to specific media or a specific cross-media transport pathway.

- ***Transformation:*** Although a number of individual PFAS, such as perfluoroalkyl acids and perfluoroalkyl ether carboxylic acids, are highly persistent due to the strength of the C-F bond, a number of polyfluorinated substances can be partially degraded via several different biological and abiotic mechanisms. Transformation of these precursors to PFAAs has been shown to occur in a variety of environmental media and can result in unexpected temporal and spatial trends in PFAS occurrence. The susceptibility of individual PFAS to transformation processes can also influence how each will bioconcentrate and bioaccumulate within various biotic species.

- ***Uptake into biota and plants:*** Once released into the environment, PFAS will migrate to both terrestrial and aquatic systems. Uptake into plants can occur within affected areas and may transfer PFAS to wildlife and humans that consume those plants. Some compounds have a propensity to bioaccumulate and then biomagnify up the food chain, with relatively low levels in invertebrates and fish and higher levels observed in animals at the top of the food chain (for example, seals, seabirds, polar bears).

As noted previously, the physical-chemical properties of PFAS, and the influence of these properties on PFAS fate and transport within environmental media, are critical in determining how these compounds behave after they are released. To date, our understanding of PFAS fate and transport has relied largely on assumptions based on these physical-chemical characteristics, even though the specific parameter values have proven challenging to estimate; however, there is an increasing amount of lab- and field-derived data that has improved the empirical basis for understanding PFAS fate and transport. This section focuses on findings from peer-reviewed studies that directly evaluated PFAS fate and transport and provided key insight on the processes described above. The material in this section is also intended to provide a technical basis for subsequent sections on site characterization (Section 10) and treatment of PFAS (Section 12).

5.2 Phase Partitioning

5.2.1 Introduction

PFAS most commonly detected in the environment typically have a carbon-fluorine tail and a nonfluorinated head consisting of a polar functional group (see Section 2.2 for more information about naming conventions and terminology). The tail is hydrophobic and generally lipophobic (attracted neither to water nor to nonpolar organic matter), while the head groups can be polar and hydrophilic (attracted to water) (Buck et al. 2011). The competing tendencies of the head and the tail can lead to a widespread yet uneven distribution in the environment. Given the heterogeneity of subsurface environments, soils with different surface charges, organic carbon, interfaces between air and water, and interfaces with water and hydrocarbon co-contaminants, multiple partitioning mechanisms should be considered when characterizing PFAS fate and transport. PFAS may also exhibit different behavior depending on concentration, such as the tendency to form micelles at high concentrations (Section 5.2.2.2). Although the structure of PFAS makes them generally oil- and water-resistant in many products (for example, dry surface coatings), in the aqueous phase, PFAS may not exhibit lipophobic tendencies, as shown by the ability of a variety of PFAS to partition to phospholipid bilayers (bacterial membranes) (Jing, Rodgers, and Amemiya 2009; Fitzgerald et al. 2018).

Important PFAS partitioning mechanisms include hydrophobic effects, electrostatic interactions, and interfacial behaviors. Electrostatic effects are a function of the charge of the polar functional group at the head of the molecule and are one of the processes that generally drive the association with organic carbon in soils. For instance, natural soils and aquifer materials often have a net negative surface charge that can repel the negatively charged heads of PFAAs, which are usually present as anions in environmental media, while attracting cationic or zwitterionic PFAS. As is the case for all surfactants, the competing nature of the head and tail groups result in accumulation along interfaces of environmental media such as soil/water, water/air, and water/nonaqueous phase liquid (NAPL) co-contaminants (Guelfo and Higgins 2013; McKenzie et al. 2016; Brusseau 2018).

5.2.2 Considerations for PFAS Partitioning

5.2.2.1 Pure Phase PFAS

Due to high aqueous solubility, PFAS occurrence as a separate phase in the environment (for example, solid PFAS, LNAPL PFAS, or DNAPL PFAS) is uncommon. Although PFAS may exist as solid salts, typical product applications involve miscible solutions that are frequently mixtures of many different compounds. Several of these compounds exhibit relatively high solubility in water (the Physical and Chemical Properties Table, Table 4-1 provided as a separate Excel file), defined by Ney (1995) as exceeding 1,000 mg/L water. For example, PFOA has a reported solubility of 9,500 mg/L at 25°C (USEPA 2017). Note that PFAS interactions with NAPL co-contaminants within the subsurface have been reported and can impact migration in the subsurface (Section 5.2.5).

5.2.2.2 PFAS Micelles and Foam Formation

A surfactant is a substance that tends to lower the surface tension of a liquid into which it is dissolved. As discussed in Section 4.2.7, the surfactant properties of some PFAS may result in the assembly of PFAS molecules into supramolecular aggregations (micelles, mixed micelles, hemi-micelles, or bilayer structures; see Figure 5-2). The surfactant properties of PFAS are also what cause collection at interfaces like the air-water interface (see Section 4.2.8 and Figure 4-1). The surfactant properties, along with heat resistance, have been exploited for applications such as AFFF, which forms a thin film of water over the fuel source.

With respect to supramolecular aggregations, there is experimental evidence that PFAS can act like ionic hydrocarbon surfactants and form micelles at a critical micelle concentration (CMC) (Pedone et al. 1997; Downer et al. 1999), and many have theorized that, also like ionic hydrocarbon surfactants, hemi-micelle formation may begin at concentrations as low as 0.001 times the CMC (Johnson et al. 2007, Yu et al. 2009). The majority of these data are focused on PFAAs, but GenX has also recently been shown to form micelles (Kancharla et al. 2022). CMCs for various PFAS are discussed in Section 4.2.7. More research is needed on the tendency for PFAS to form traditional micelles (oil-in-water emulsions), since there is some data that suggest PFAS supramolecular aggregation may not be directly analogous to ionic hydrocarbon surfactant behavior (Costanza et al. 2019 and discussed in Section 4.2.7). Additionally, the interrelated functions of several environmental variables (presence of co-contaminants, ionic concentration, pH, etc.) present additional complexities that research has only begun to address.

Because the known CMCs of PFAAs are much greater than typical environmental concentrations (with the exception of possible AFFF source releases), some researchers have concluded that the behavior of PFAAs at the CMC likely has little practical relevance (Horst et al. 2018; Brusseau et al. 2018). However, like ionic hydrocarbon surfactants, hemi-micelle formation of PFAAs may begin at concentrations as low as 0.001 times the CMC (Johnson et al. 2007; Yu et al. 2009), which is potentially relevant to the understanding of PFAA sorption for both the creation of potential treatment technologies and environmental fate and transport. The interaction of supramolecular aggregations of PFAAs with both charged and hydrophobic surfaces can affect the magnitude of sorption, but the extent and even the direction of influence is dependent on many factors (Deng et al., 2012; Zhang, Zhang and Liang, 2019; Du et al. 2014). For example, adsorption of the hydrophilic portions of PFAAs (that is, the “heads”) onto positively charged absorbent surfaces can contribute to the formation and accumulation of hemi-micelles on surfaces. Simultaneously, it is possible that hemi-micelles and even micelles can block the intraparticle pores of porous surfaces, reducing the magnitude of sorption.

In surface water, PFAS may accumulate within the surface micro layer (SML) that is defined as the thin layer (50 µm) of water in contact with the ambient air (Section 16.5.5). This accumulation can also lead to foam formation above the surface water due to winds, waves, or other turbulent forces that introduce air into the water. In these cases, the presence of natural dissolved organic carbon within the water body can also enhance foam formation and contribute to enrichment of PFAS in these foams even at PFAS concentrations that are below reported CMCs (Schwichtenberg et al. 2020). This foam is different from AFFF because it is likely caused by the aggregation of dissolved-phase PFAS followed by agitation within a surface water body. As discussed in the Surface Water Foam Section (Section 16.5), the formation of this type of PFAS-containing foam above the surface of the water has been sampled and analyzed near or downgradient of areas where PFAS have been released (MI EGLE 2021).

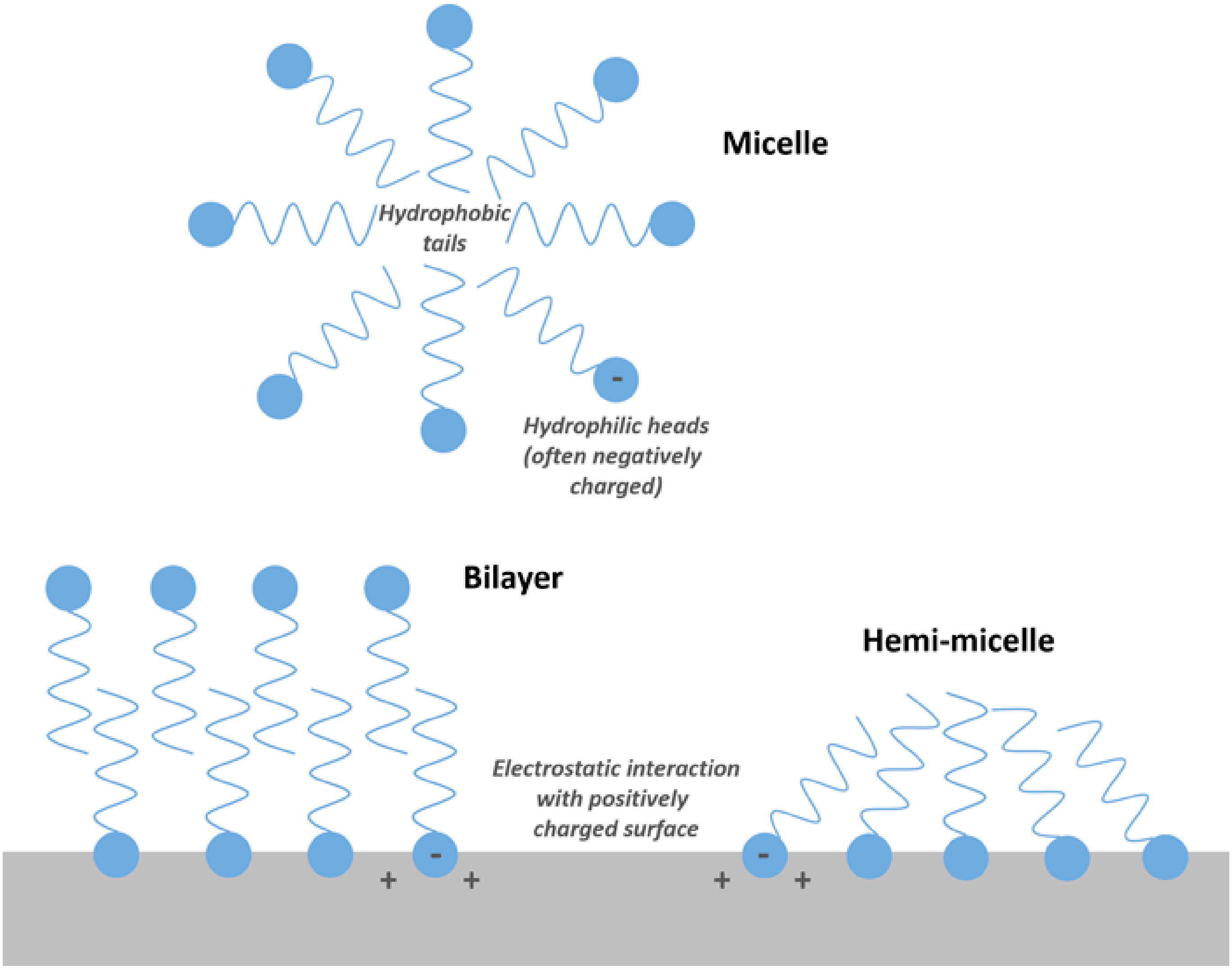


Figure 5-2. Illustration of the formation of PFAS micelles, hemi-micelles, and bilayers. Also shown is an example of aggregation at a positively charged surface. Note that the opposite effect (electrostatic repulsion of PFAS) can occur if the surface is negatively charged.
Source: D. Adamson, GSI. Used with permission.

5.2.3 Partitioning to Solid Phases

PFAS can partition to a number of different solid-phase materials, including soils and sediments (Higgins and Luthy 2006), biosolids (Venkatesan and Halden 2013), sewage solids (Ebrahimi et al. 2021), iron oxides in acidic environments (Campos-Pereira et al. 2020), and organic matter (Fitzgerald et al. 2018). Partitioning to solids results in retention of PFAS on the solids, thereby reducing or retarding leaching from vadose zone sources and retarding PFAS migration in the saturated zone. Conversely, PFAS may also partition to mobile colloids, resulting in facilitated transport rather than retardation (Brusseau et al. 2019), which may be particularly important in environments where colloidal transport is more likely to occur, such as sediment transport and deposition in moving water and environments undergoing wet-dry or freeze-thaw cycles (Borthakur et al. 2021). Section 5.3.4.2 discusses surface water/sediment interactions.

In addition, published studies of migration of PFAS in bedrock aquifers are scarce, but many of the processes controlling sorption in soils will be limited in fractured crystalline bedrock aquifers, resulting in potential for migration of PFAS over longer distances once plumes migrate to the bedrock aquifer.

5.2.3.1 Partitioning Processes

As discussed in Section 5.2.1, partitioning of PFAS to solids and soils is widely studied and is thought to occur through two primary processes: 1) sorption through electrostatic interactions, and 2) sorption to organic matter via hydrophobic interactions (Higgins and Luthy 2006) (see Sections 5.2.1 and 5.2.2 for a discussion of interfacial behavior, another subset of partitioning). The relative contribution of each process can vary depending on the PFAS, soil composition, surface chemistry, ion concentration, and other geochemical factors. Because the multitude of PFAS span a broad range of compositions and carbon chain lengths, PFAS partitioning to solids can be variable and uncertain, and dependent on site-specific factors.

5.2.3.2 Electrostatic Interactions

The contribution of electrostatic interactions to partitioning is highly dependent on soil type and soil chemistry (particularly pH and the presence of polyvalent cations). Most soils contain both fixed-charge and variably charged surfaces, such that the net charge on the soil, as well as the charge of functional groups of individual PFAS, can be strongly influenced by pH. For example, the net negative charge on most clay minerals can result in electrostatic interactions with cationic functional groups that are present on some PFAS (Barzen-Hanson et al. 2017).

Changes in pH potentially impact these electrostatic processes by altering surface charges, or possibly the ionic nature of the PFAS (Nguyen et al. 2020). Lower pH values and higher calcium concentrations in soil solutions have been associated with increased sorption of anionic PFAS such as PFOS and other PFAAs (Higgins and Luthy 2006), although the buffering capacity of some soils (for example, carbonate minerals) may mitigate fluctuations in pH. Furthermore, increased concentrations of some polyvalent cations, such as Ca^{2+}, Mg^{2+} Fe^{2+}, which sorb strongly to permanent charge sites on clay minerals, can lead to increased partitioning to soil for some PFAS (Higgins and Luthy 2006; McKenzie et al. 2015), although the effect on cationic and zwitterionic PFAS can vary widely, which has been attributed to charge differences in the PFAS functional groups (Mejia-Avendaño et al. 2020). Although the literature has attributed anionic PFC sorption to iron-oxide materials, the dominant parameter influencing sorption in the Higgins and Luthy (2006) study was organic matter content.

5.2.3.3 Sorption to Organic Matter

In Higgins and Luthy (2006), where organic carbon ranged from 0.56% to 9.66%, and other studies, organic carbon was found to be the dominant parameter driving the extent and kinetics of PFAS sorption (Higgins and Luthy 2006; Li et al. 2018; Li et al. 2019; Sima and Jaffe 2021; Wei et al. 2017). PFCAs and PFSAs tend to associate with the organic carbon fraction of soil or sediment (Higgins and Luthy 2006; Guelfo and Higgins 2013) in the saturated and unsaturated zones, although as anions at environmental pH values (see Section 4.3.2), they are relatively mobile in groundwater (Xiao et al. 2015).

Sorption to organic carbon generally increases with increasing perfluoroalkyl tail length, which is also associated with increased hydrophobicity (Higgins and Luthy 2006; Guelfo and Higgins 2013; Sepulvado et al. 2011; Campos Pereira et al. 2018; Cai et al. 2022), indicating that the short-chain PFSAs (for example, PFBS) and PFCAs (for example, PFBA) are less retarded than their long-chain counterparts (PFOS and PFOA, respectively). In addition, PFSAs tend to sorb more strongly than PFCAs of equal chain length (Higgins and Luthy 2006), and linear isomers are more sorptive than branched isomers (Karrman et al. 2011). Although simple correlations with organic carbon appear to be insufficient to predict PFAS partitioning coefficients, it is important to evaluate what PFAS are present and to quantify the fraction of organic carbon (f_{oc}) to model PFAS sorption as a potential predictive tool for estimating PFAS retention and retardation for certain PFAS.

5.2.3.4 Partitioning Coefficients

Table 4-1, provided as a separate Excel file, presents the range of available organic carbon partitioning coefficients (K_{oc}) for PFAS commonly observed in the environment. K_{oc} is a soil organic carbon-normalized adsorption coefficient and may serve as a useful parameter for evaluating potential retardation. However, this parameter does not directly capture any contributions from electrostatic interactions (Higgins and Luthy 2006), meaning that, depending on the PFAS being evaluated, estimating sorption by measuring the f_{oc} in soil in combination with a literature-derived K_{oc} value may underestimate (or in some cases, overestimate and the associated error could be significant) retardation. Additional site-specific information such as pH, presence of polyvalent cations, and electrostatic processes retardation coefficients, are mentioned in Section 10.4.2.

Li, Oliver, and Kookana (2018) compiled data from several literature studies and concluded that the bulk partitioning coefficients (Kd) estimated for various PFAS were best correlated with organic carbon content and pH. However, a study by Barzen-Hanson et al. (2017) showed a general lack of correlation between soil parameters (such as organic carbon) and partition coefficients derived for some PFAS, such as anionic fluorotelomer sulfonates as well as several cationic and zwitterionic PFAS. Anderson, Adamson, and Stroo (2019) reviewed field data from a large number of AFFF release sites and deduced that organic carbon significantly influences PFAS soil-to-groundwater concentration ratios, and they used statistical modeling to derive apparent K_{oc} values for 18 different PFAS based on these data.

The use of partitioning coefficients to estimate sorption requires the assumption of steady state conditions, which rarely occur in natural systems. In idealized systems, PFAS sorption kinetics vary by functional group and carbon chain length, as well as soil composition, but equilibrium is generally achieved over several days to weeks (Xiao et al. 2017; Schaefer et al 2021). Lab-based and modeling studies have established that partitioning of PFAS cannot be easily modeled using equilibrium sorption parameters in some cases due to rate-limited sorption considerations (Guelfo et al. 2020;Brusseau 2020). Lab-based Kd values (derived using adsorption isotherms) could likely underestimate the impact of sorption during fate and transport modeling (for example, by underestimating the retardation factor or by overestimating the extent of desorption) (Schaefer et al. 2021). Schaefer et al. (2021) observed that the extent of desorption from soils exposed to PFAS decades ago generally was substantially less than predicted by published $K_{oc}f_{oc}$ relationships for the PFAS studied, suggesting that desorption from old PFAS releases may have a less pronounced impact on underlying groundwater, particularly for shorter chain PFAS. Schaefer et al. (2022) noted that much of the PFAS present in soils historically impacted with AFFF in their study was not readily leachable using the selected desorption procedure(s).

5.2.3.5 Nonlinear Sorption, Hysteresis, and Mass Transfer Limitations

Sorption processes of PFAS can be impacted by nonlinear sorption, hysteresis, and mass-transfer limitations. Nonlinear sorption typically implies that PFAS will sorb more strongly at low PFAS concentrations than high concentrations. Counter to typical nonlinear sorption tendencies, at least one field study observed greater sorption at higher concentrations (Anderson et al. 2022). There is also some evidence that desorption may occur more slowly than sorption for certain PFAS, which is hypothesized to be the result of entrapment and diffusion limitations (Higgins and Luthy 2006; Chen et al. 2016; Zhi and Liu 2018; Xiao et al. 2019). Several studies have observed that select PFAS can be subject to rate-limiting sorption (for example, diffusion limited), meaning that desorption of a portion of the sorbed PFAS will occur more slowly than other portions (Xiao et al. 2019; Schaefer et al. 2021). For example, Brusseau et al. (2019) showed that PFOS exhibited nonideal sorption/desorption behavior (tailing). Kinetic desorption modeling in the study indicated “that the rate of desorption was proportional to the PFAS aqueous diffusivity” (Schaefer et al. 2021), supporting the hypothesis that diffusion may also limit the rate of release from soil. Any portion of the released PFAS that is strongly retained within sediments or the soil matrix may be more persistent but likely less bioavailable and less subject to migration. This hysteresis effect on a portion of the sorbed PFAS in soils may also be a contributor to sorption included in the rationale for natural attenuation of some PFAS that was evaluated by Newell et al. (2021).

PFAS partitioning due to electrostatic interactions has been shown to be nonlinear in some cases; Xiao et al. (2019) demonstrated that the variation in the coefficient of sorption for several zwitterionic PFAS to soils (for example, loams, clay loams) implies an increase in sorption as the PFAS concentrations decreased. The significant nonlinearity of zwitterionic PFAS observed by Xiao et al. (2019) also exhibited a high degree of hysteresis that was not related to soil organic matter or surface complexation and was postulated to be due to entrapment. For PFAS such as PFOA and PFOS that are anionic at environmentally relevant pH, measuring the anion exchange capacity in representative soils may serve as an indicator of the importance of electrostatic interactions with minerals. However, because soil pH can range considerably, pH can also serve as a useful measure of potential PFAS mobility. Measurements of cation concentrations or the ionic strength of an aqueous solution may also provide useful information on the potential contribution of electrostatic attraction to enhanced partitioning.

The findings discussed within this subsection are particularly relevant for strongly sorbing long chain PFAS such as PFOS (Chen et al. 2016) and sorbed PFAS that exhibit a high degree of hysteresis, such as zwitterionic PFAS, and have important implications for PFAS fate and transport such as leaching from soil to groundwater (see Section 5.3.3), migration and retardation in the saturated zone, and whether sorption can function as a form of natural attenuation (Newell et al. 2021, Newell et al. 2021) (see Sections 10.4.7 and 10.4.8, Table 10-1, and 12.6.8 for further discussion). Additional research is needed to further evaluate if any of these bulk parameters can be used predictively for fate and transport studies (Barzen-Hanson et al. 2017) and to understand the parameters’ role in irreversible sorption of PFAS that have been adsorbed for decades. Current research supports the conclusion that simple correlations of sorption with organic carbon or pH are insufficient to reliably predict PFAS partitioning coefficients for many PFAS. Thus, in the absence of a reliable model that predicts the role of different mechanisms on the extent of sorption (and hysteresis), site-specific data may be more appropriate for understanding PFAS transport (Knight et al. 2019; Anderson et al. 2016; Li, Oliver, and Kookana 2018) and considerations for pump-and-treat systems. Other considerations, such as air-water interface interactions, are discussed in Section 5.2.4.1.

5.2.4 Partitioning to Air

As discussed in greater detail in Section 4.2, reliable data on physical properties that relate to PFAS volatilization, such as vapor pressure and Henry’s law constants (K_{aw}), are currently limited but the data set is growing. Additionally, volatilization from water to air of acidic PFAS, such as PFAAs, is affected by pH-dependent, aqueous phase dissociation from more-volatile acidic species to less-volatile anionic species (Kaiser et al. 2010). Measured vapor pressures are available for some select PFAAs, including the acidic forms of PFOA, perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUnA), and perfluorododecanoic acid (PFDoDA) (Barton, Botelho, and Kaiser 2008; Kaiser et al. 2005), as well as FTOHs (Krusic et al. 2005). Henry's law constants (K_{aw}) for several PFAS are reported in Section 4.2.6. As noted by the values provided in Table 4-1, Kaw can vary over multiple orders of magnitude for a given PFAS; underlying causes for the large range in reported values are not clear, but may relate to variability in measurement conditions. For some PFAS that are acidic at environmentally relevant pH, such as PFOS and PFOA, the reported vapor pressures are low and reported water solubilities are high, limiting volatilization from water to air (USEPA 2000). Other PFAS, such as FTOHs, have specific functional groups that tend to impart greater volatility. In one study performed by Roth et al. (2020), agitation of AFFF was demonstrated to release gas-phase PFAS, reportedly including PFOA. These experiments were performed in a controlled lab setting and resulted in detectable concentrations of five FTOHs and 10 PFCAs above background laboratory air concentrations. The potential for this type of partitioning to occur in field settings was not evaluated, and the veracity of the PFOA detections has been debated (Titaley, De la Cruz, and Field 2020; Roth et al. 2020).

Under certain conditions, particularly within industrial stack emissions, or during fire suppression, incineration, or combustion, PFAS can be emitted and transported through the atmosphere. This can include volatiles like FTOHs that may be present in the gas phase (Thackray, Selin, and Young 2020) and anionic PFAS that may be sorbed to particulates (Ahrens et al. 2012). In the latter case, transport occurs through the association of anionic PFAS with airborne aerosols and other small particulates rather than direct partitioning to the gas phase. For example, PFOA and PFOS have been detected in airborne particulate matter in both urban and semirural areas, with PFOA dominant in the smaller, ultrafine particles and PFOS dominant in the larger, coarser fractions (Dreyer et al. 2015; Ge et al. 2017). These studies show that some PFAS can be adsorbed to particulates, likely reflecting the influence of local diffuse sources. As discussed in Section 5.3, removal of airborne PFAS can occur via wet and dry deposition processes that scavenge particle-bound PFAS or gaseous PFAS that has partitioned into water droplets (Barton, Kaiser, and Russell 2007; Dreyer et al. 2010). Wet deposition refers to the wash out of PFAS by rain droplets, where PFAS drops to the ground with no transfer of PFAS to the air (Barton, Kaiser, and Russell 2007). This has been shown to be a relevant mechanism for influencing airborne transport within a few kilometers downgradient of a major manufacturing source (Barton, Kaiser, and Russell 2007; Davis et al. 2007). Dry deposition is a naturally occurring process that depends on prevailing environmental conditions and particle characteristics. Since these deposition processes remove PFAS from the atmosphere, they can influence the location and magnitude of PFAS deposition to terrestrial and aquatic environments.

Kaiser et al. (2010) demonstrated the partitioning of PFOA to workplace air from water and dry surfaces. Partitioning to air from these substrates appears to depend on conditions within the substrate, with lower pH environments contributing more PFOA mass to air. The protonated acid form of PFOA has an elevated vapor pressure, which may explain these observations (Kaiser et al. 2005). Interestingly, these authors showed that more PFOA partitions from dry surfaces than from water and may contribute significantly to workplace exposures.

5.2.4.1 Partitioning to Air/Water Interfaces

As described above, PFAS often exhibit surfactant behavior because many display hydrophobic and hydrophilic properties. The impacts of these properties on transport are complex and are being actively investigated. By design, many PFAS will lower the interfacial tension and preferentially form films at the air-water interface (if present at elevated concentrations), with the hydrophobic carbon-fluorine (C-F) tail oriented toward the air and the hydrophilic head group dissolved in the water (Krafft and Riess 2015) (Figure 4-1). This behavior influences aerosol-based transport and deposition, and suggests that accumulation of PFAS at water surfaces will occur (Prevedouros et al. 2006).

This preference for the air-water interface has important implications for PFAS transport in the vadose zone, where unsaturated conditions provide significant air-water interfacial area (Brusseau 2018; Brusseau et al. 2019; Brusseau and Guo 2022). This includes the potential for enhanced retention in the vadose zone and the capillary fringe, which are the subject of significant ongoing research. For example, Brusseau (2018) showed that adsorption of PFOS and PFOA at the air-water interface can increase the retardation factor for aqueous-phase transport, accounting for approximately 50% of the total retention in a model system (well-sorted sand) with 20% air saturation.

As a result, air-water partitioning may contribute to retardation of PFAS in unsaturated soils. Using field data, Anderson, Adamson, and Stroo (2019) reported that soils with higher clay contents were associated with lower soil-to-water concentration ratios for multiple PFAS. The authors surmised that perhaps the more likely explanation was that the higher water content within these clay-rich zones (relative to other depth-discrete zones with more coarse-grained material) decreased the air/water interfacial area available for PFAS partitioning and thus decreased overall soil retention. This pattern is also consistent with the potential for negatively charged clay surfaces to reduce anionic PFAS adsorption through electrostatic repulsion. Guo, Zeng, and Brusseau (2020) highlighted the influence of soil type on air-water interfacial accumulation as a retention mechanism in a modeling study that demonstrated retardation factors for PFOS under their experimental conditions as between 233 and 1,355 in sands and 146 and 792 for finer-grained soils. This was attributed to weaker capillary forces in the sands that resulted in lower water contents and thus more air-filled pore space to promote PFAS partitioning. Note that the simulations performed by Guo, Zeng, and Brusseau (2020) examined only PFOS and did not use field-derived input parameters, so caution should be exercised when generalizing these results to the broader family of PFAS. In addition to the influence of soil type described above, ionic strength has been shown to affect air-water interfacial partitioning whereby PFAS retardation within unsaturated soils appears to be enhanced with increasing salinity (Lyu and Brusseau 2020; Costanza, Abriola, and Pennell 2020; Le et al. 2021).

The tendency for PFAS to accumulate at air-water interfaces has the potential to significantly influence mass retention and soil-to-groundwater leaching, as discussed further in Section 5.3.3.

This has stimulated interest in incorporating these processes into CSMs, as well as predictive fate and transport models. Estimates of the air-water interfacial area and the constituent-specific air-water adsorption coefficients, as well as direct measurements of mass discharge to groundwater, can help provide a quantitative basis for these types of models (Brusseau 2019; Guo, Zeng, and Brusseau 2020). In general, air-water adsorption coefficients for an individual PFAS decrease as the concentration increases, and the process appears to be nonlinear (for example, Freundlich-type partitioning) (Schaefer et al. 2019). Air-water adsorption coefficients also tend to increase as the number of perfluorinated carbons increases (Brusseau 2019; Schaefer et al. 2019) (see Section 4.2). This means that when PFAS are released as a multicomponent mixture, these processes will influence each compound to a different extent, with less retention of shorter chained PFAS (for example, PFBS, PFPeA) than longer chained PFAS (for example, PFOS, PFDA, PFNA) (Silva, Martin, and McCray 2021). Silva, Martin, and McCray (2021) also showed that preferential adsorption of the more surface-active PFAS within a mixed release is expected to reduce the adsorption of the other, less surface-active PFAS in the mixture. This type of competitive adsorption would influence the relative breakthrough times for different PFAS within a mixed release.

The potential retention of PFAS in the vadose zone due to adsorption at the air-water interface is an important component that should be addressed in the CSM, but the retention of PFAS is based on site-specific factors. At sites with shallow groundwater tables, or sites where the water content within the vadose zone soils is typically low, air-water interfacial partitioning may not be particularly relevant. As such, detailed site investigations are critical to understanding how these processes influence PFAS migration through the vadose zone of a specific site. For example, an extensive study of PFAS concentrations in soil at contaminated sites indicated significant retention of PFAS in the vadose zone over long periods of time, but vertical migration of PFAS to the water table was also evident, resulting in detectable PFAS in groundwater at a majority of the investigated sites (Brusseau 2020).

5.2.5 Partitioning into NAPL Co-Contaminants

PFAS and petroleum hydrocarbon fuels in the form of NAPLs may commingle at fire training areas, fire response sites, and other locations where fuels were used or disposed concurrently with PFAS-containing materials. In these settings, the released petroleum hydrocarbon fuel forms a NAPL into which the PFAS may partition and accumulate along the NAPL/water interface (Brusseau 2018). These processes may result in increased PFAS mass retained in NAPL source zones, increased PFAS sorption onto the NAPL/water interface and resulting retardation, and greater persistence of PFAS (Guelfo and Higgins 2013; McKenzie et al. 2016; Brusseau 2018). The contribution of this process relative to other PFAS partitioning mechanisms (for example, solid phase, air-water interface) will vary based on site-specific conditions. However, several studies have suggested that the PFAS mass accumulating at the NAPL-water interface is likely to be less than that at the air-water interface in systems where all these phases are present (Brusseau 2019; Silva et al. 2019; Costanza, Abriola, and Pennell 2020).

The presence of NAPL may have other effects on PFAS. The presence of biodegradable NAPL, such as petroleum light nonaqueous phase liquids (LNAPLs), may significantly alter the biogeochemistry and oxidation-reduction conditions in the subsurface. For example, subsurface petroleum LNAPLs remaining from a petroleum-based fire tend to locally deplete the concentration of oxygen and other electron acceptors and elevate the concentration of methane. The LNAPL creates a localized zone of anoxic reducing conditions where PFAS aerobic transformation processes are inhibited, and anaerobic transformation processes may occur. These transformation processes are discussed in more detail in Section 5.4.

5.3 Media-Specific Migration Processes

The potential impacts of processes such as diffusion into low-permeability matrices, atmospheric transport, and leaching from soil to groundwater are described. Unlike partitioning processes, which involve the exchange of chemicals between media, the following describes processes that occur within specific media that may be important considerations for PFAS migration.

5.3.1 Diffusion In and Out of Lower Permeability Materials

Diffusion is the movement of molecules in response to a concentration gradient. Diffusion in groundwater is often ignored because diffusion rates are slow relative to advection. In low permeability materials, migration of contaminants is mainly driven by molecular diffusion, and advective effects may be less dominant depending on the magnitude of hydraulic gradient. In the vicinity of groundwater pumping wells, analysis might need to be conducted by taking into account both the effects of molecular diffusion and advection simultaneously (Al-Niami and Rushton 1977). However, contaminant mass in groundwater can diffuse into the pore space of lower permeability soils or bedrock. Back-diffusion out of these low permeability materials may result in the long-term persistence of PFAS in groundwater even after source removal and remediation. Due to the lack of degradation of PFCAs and PFSAs, back-diffusion of these PFAS is also likely to be a more significant process than for conventional contaminants such as chlorinated solvents. Adamson et al. (2020) reported that approximately 82% of the total mass of PFAS measured at an AFFF site was found within soils that were classified as lower permeability. This included 91% of the polyfluorinated precursor mass, most of which was encountered in the vicinity of the presumed source area. The mass distribution at this site confirmed that diffusion into lower permeability soils had occurred and demonstrated that this process can contribute to long-term retention of PFAS. The relative impact of PFAS accumulation at the air-water interface was not fully investigated in this study, as the water table was very shallow, and the unsaturated/saturated transition zone was likely disturbed during excavation. PFAS may also diffuse into site materials such as concrete. For example, Baduel, Paxman, and Mueller (2015) reported that PFAS had penetrated 12 cm into a concrete pad at a fire training area, and diffusion was identified as a contributing process.

The potential impacts of diffusion on PFAS persistence in natural soils are a topic of ongoing research. Determining appropriate diffusion coefficients for the range of PFAS that may be present following a release is a key element in understanding how this process impacts PFAS persistence. Schaefer et al. (2019) reported experimentally derived diffusion coefficients for 9 different PFAAs and showed that aqueous diffusivity values decreased as the PFAS molar volume increased. However, this relationship was nonlinear due to the complex molecular interactions of fluorinated compounds, and the values showed reasonable agreement with some but not all comparable methods of deriving diffusion coefficients. In addition, the relative rates of diffusion of PFAS with differing charges (for example, anionic vs. zwitterionic/cationic) is a potential concern given that porous media particles may also be charged. In the study by Adamson et al. (2020) described above, 93% of the polyfluorinated mass that had diffused into the lower permeability zones was zwitterionic and/or cationic; a smaller percentage of the anionic polyfluorinated mass was found in these zones. Higher organic carbon and favorable electrostatic interactions likely contributed to further retention of PFAS. The results of this study suggest that matrix diffusion may enhance long-term retention and reduce PFAS mass discharge rates by transferring PFAS mass to less-transmissive zones.

5.3.2 PFAS Transport via Air

Many PFAS have been measured in air (Section 6.1) and are known to be released to air from a variety of sources (Section 2.6). Air serves as an important transport medium for PFAS, allowing PFAS to disperse in all wind directions, contributing to global dispersion, and leading to localized PFAS deposition to soils and surface water in the vicinity of emission sources (for example, (Shin et al. 2012)) which is of potential concern to site investigations.

The role of atmospheric transport depends on PFAS-specific properties such as vapor-particle partitioning, and mechanisms can be complex. Aerosols, representing a suspension of solid particles and liquid droplets in the air, provide a variety of environmental media and surfaces within or upon which a range of PFAS partitioning behavior can be observed. For example, McMurdo et al. (2008) described the release of concentrated PFAS aerosols from a water surface (where PFAS are often located). Airborne transport of PFAS is a potentially relevant migration pathway due to the common types of industrial release (for example, stack emissions). The specific means of PFAS releases from industrial sources have not been extensively studied, but could involve processes such as droplet mobilization from drying and agitation of liquid surfaces.

PFAS and other harmful air pollutants, including fluorinated products of incomplete combustion (PICs), can be released into the air from facilities that treat PFAS in air and solid media, such as incinerators, cement and lightweight aggregate kilns, sewage sludge incinerators, municipal waste combustors, soil desorbers, pyrolyzers, and spent carbon reactivation facilities (Krug et al. 2022; Riedel et al. 2021; Stoiber, Evans and Naidenko 2020). Few comprehensive waste characterization or full-scale demonstration studies have been conducted to document the performance of these treatment facilities in removing and destroying PFAS. In one recent study conducted under typical operations at a full-scale spent carbon reactivation facility, researchers reported full removal of PFAS compounds from the spent carbon and >99.99% destruction of PFAS compounds through the reactivation facility furnace and air pollution control systems (DiStefano et al. 2022). The importance of other sources, such as combustion emissions or windblown foam from fire training and fire response sites, may need to be assessed. Section 12.4 includes additional information about incineration.

Once airborne, PFAS can occur in a gaseous state or be incorporated within particulate matter or other aerosols suspended within the air. The composition of the gas phase will be dependent on the industrial process(es) contributing to emissions. Neutral volatile precursor compounds, such as FTOHs, are often the dominant PFAS present in the gas phase (see Section 17.1) and can account for at least 80% of the total PFAS mass in ambient air in an urban area (Ahrens et al. 2012).

Over the open oceans and in remote regions, FTOHs also dominate neutral PFAS and almost all are present in the gas phase (Bossi, Vorkamp, and Skov 2016; Lai et al. 2016; Wang et al. 2015; Dreyer et al. 2009). In contrast, ionic PFAS, such as PFOA and PFOS, characterized by low vapor pressure and high water solubility, tend to be the dominant species found in airborne particulate matter. PFOA is associated with smaller, ultrafine particles, while PFOS is associated with larger, coarser fractions in both urban and semirural areas (Ge et al. 2017; Dreyer et al. 2015). Wet and dry deposition are the major mechanisms of removal of PFAS from the atmosphere and can occur from the scavenging of particle-bound PFAS or partitioning of gaseous PFAS to water droplets (Dreyer et al. 2010; Barton, Kaiser, and Russell 2007; Hurley et al. 2004). PFAS are commonly found in precipitation (rain and snow), with wet and dry deposition estimated to occur on a time scale of a few days (Chen et al. 2016; Lin et al. 2014; Taniyasu et al. 2013; Zhao et al. 2013; Dreyer et al. 2010; Kwok et al. 2010; Liu et al. 2009; Barton, Kaiser, and Russell 2007; Kim and Kannan 2007; Hurley et al. 2004). Certain PFAS, such as PFOS, have been found to persist in fine particulate matter (PM2.5) in the United States nearly 20 years after production was phased out, which confirms the presence of continuing sources (Zhou et al. 2021).

Atmospheric deposition can occur as dry or wet deposition, both of which are relevant for PFAS (Barton, Kaiser, and Russell 2007, 2010; Dreyer et al. 2010; Taniyasu et al. 2013). During dry deposition, PFAS that are preferentially associated with liquid or particle phases in air (aerosols) can be naturally deposited onto surfaces via settling, diffusion, or other processes. When precipitation contributes to washout of these PFAS-containing aerosols, the process is known as wet deposition. Wet and dry deposition are the major mechanisms for removal of PFAS from the atmosphere and can occur from the scavenging of particle-bound PFAS or partitioning of gaseous PFAS from water droplets (Dreyer et al. 2010; Barton, Kaiser, and Russell 2007; Hurley et al. 2004). Deposition is considered a sink term for the atmosphere because mass is removed and the potential for longer range atmospheric transport is reduced. However, this same process thus represents a potential source of PFAS to terrestrial and aquatic environments. Once settled, PFAS adsorbed onto soils or other surfaces (including indoor surfaces) can be resuspended when particulate matter is disturbed by wind or other physical means. See Section 6.1 for further discussion of atmospheric deposition of PFAS.

Short-range atmospheric transport and deposition can result in PFAS contamination in terrestrial and aquatic systems near points of significant emissions, impacting soil, groundwater, and other media of concern (Davis et al. 2007). PFAS can migrate downward from surficial soils into the groundwater table via leaching processes described in Section 5.3.3. Evidence of releases has been observed in areas where hydrologic transport could not plausibly explain the presence of PFAS in groundwater, with the extent of contamination reaching several miles from sources and in distribution patterns independent of regional hydrology (Frisbee et al. 2009; Post 2013; Post, Cohn, and Cooper 2012; NYS DOH 2016; NH DES 2017; VT DEC 2016). Air emissions from industrial sources can cause contamination of drinking water sources and pose a potential increased risk to human health in communities over wide areas surrounding the emissions source (Schroeder, Bond, and Foley 2021). Releases of ionic PFAS from factories are likely tied to particulate matter (Barton et al. 2006), which settles to the ground in dry weather and is are also wet-scavenged by precipitation (Slinn 1984; Sehmel 1984). Key variables that should be used to predict impacts to groundwater wells include the rate of PFAS air emissions and distance from upwind sources, prevailing wind direction, soil characteristics, and well depth (Roostaei et al. 2021). In a study using a statewide data set to model PFAS in private wells (n~2300), researchers found that proximity to point sources, including plastics, rubber, and textile industries, was the most important predictor of impacts, with groundwater recharge, precipitation, soil sand and clay content, and hydraulic conductivity as secondary predictors (Hu et al. 2021).

Predictive models have been applied to estimate PFAS deposition (D’Ambro et al. 2021; Shin et al. 2012). The American Meteorological Society/USEPA regulatory model AERMOD system contains modules to estimate both wet and dry deposition of both aerosols and gases (USEPA 2016). The Community Multiscale Air Quality (CMAQ) model has also been applied to investigate the atmospheric fate and transport of PFAS emissions (including GenX) from a fluoropolymer manufacturing facility in North Carolina (D’Ambro et al. 2021). In this study, researchers predicted that 5% by mass of total emitted PFAS and 2.5% of total GenX are deposited within ~150 km of the source, with the majority of emissions being transported beyond 150 km (D’Ambro et al. 2021). Model validation is important and where uncertainty exists, model predictions should be interpreted with caution. Nevertheless, the model may be useful in understanding the pattern of PFAS found in soil and groundwater in the vicinity of PFAS emission sources (Shin et al. 2012). Key input parameters for emissions from a smokestack or vent include the height of the release point and adjacent structures, source emission rates and particle size distributions, stack effluent properties (temperature and volumetric flow rate), meteorological data, local topography, and land use characteristics. A number of states are actively engaged in the application and review of air models for evaluating the impact of PFAS emissions from industrial sources and can provide valuable information on their use and the interpretation of findings.

Long-range transport processes are responsible for the wide distribution of neutral and ionic PFAS across the earth as evidenced by their occurrence in biota, surface snow, ice cores, seawater, and other environmental media in remote regions as far as the Arctic and Antarctic (Szabo et al. 2022; Langberg et al. 2022; Joerss et al. 2020; Yeung et al. 2017; Bossi, Vorkamp, and Skov 2016; Kirchgeorg et al. 2016; Rankin et al. 2016; Wang et al. 2015; Codling et al. 2014; Wang et al. 2014; Kirchgeorg et al. 2013; Kwok et al. 2013; Benskin, et al. 2012; Cai et al. 2012, 2012, 2012; Ahrens, Xie, and Ebinghaus 2010; Dreyer et al. 2009; Young et al. 2007). Geochemical modeling of the contributions of atmospheric and oceanic inputs in the Arctic suggests that atmospheric inputs may account for as much as 34%–59% of measured PFOA concentrations in the polar mixed layer (PML) (Yeung et al. 2017). Declining trends in the concentration of PFSAs in higher trophic arctic mammals has been largely attributed to reductions in long-range atmospheric transport as a result of industrial phaseout of certain PFAS (Routti et al. 2017). Distribution of PFAS to remote regions far removed from direct industrial input is believed to occur from both (1) long-range atmospheric transport and subsequent degradation of volatile precursors and (2) transport via ocean currents and release into the air as marine aerosols (sea spray) (Lin et al. 2021; Casas et al. 2020; Joerss et al. 2020; DeSilva, Muir, and Mabury 2009; Armitage et al. 2009; Wania 2007; Ellis et al. 2004).

5.3.3 Leaching

PFAS present in unsaturated soils are subject to downward leaching during precipitation, flooding, or irrigation events that promote dissolution and migration of contaminant mass (Sepulvado et al. 2011; Ahrens and Bundshuh 2014; Sharifan et al. 2021). This process can result in PFAS transport from surface soils to groundwater and surface water because PFAS releases often involve surface applications (for example, AFFF and biosolids) or atmospheric deposition (Borthakur et al. 2022; Gellrich, Stahl, and Knepper 2012; Anderson, Adamson, and Stroo 2019; Galloway et al. 2020).

PFAS migration from shallow soils to groundwater is influenced by several interacting processes, which may enhance or limit PFAS leaching rates. The leaching potential will be enhanced in areas with high water infiltration rates, which may include natural water sources such as precipitation or human-made sources such as irrigation. The thickness of the unsaturated zone (depth to water table) will also affect leaching potential. These factors are consistent with other (non-PFAS) contaminants in shallow soils. Conversely, several PFAS-specific processes, as described in Section 5.2, potentially limit the extent of PFAS leaching from shallow soil to groundwater. These include partitioning of PFAS to solid phases (for example, soil particles), adsorption at the air-water interface, and partitioning to NAPL. As a result, any soil properties that enhance the potential relevance of PFAS-sorptive processes may limit soil-to-groundwater leaching. This includes elevated levels of organic carbon, surface area and surface charge, increasing air content, and higher ionic strength within the vadose zone (Guelfo and Higgins 2013). The structural properties of the individual PFAS will also influence their transport, including the tendency for longer chain PFAAs to be less soluble and exhibit larger partitioning coefficients than shorter-chain PFAAs. In addition, several of these partitioning processes within the vadose zone have been shown to be nonlinear, which means that their relative contribution to leaching may change over time as concentrations change as a result of dilution and transformation (Zeng and Guo 2021). Finally, site conditions that influence the degree of flushing (for example, precipitation rates and depth to groundwater) should be considered when evaluating the potential for PFAS to leach from soil to groundwater.

While our understanding of these vadose zone processes continues to evolve, there are several possible implications that may be relevant for managing sites where PFAS have been released:

- These processes can affect the rate at which some PFAS migrate through the vadose zone to groundwater (breakthrough). As with hydrophobic partitioning, the relative importance of air-water interfacial partitioning is highly dependent on hydrogeologic and geochemical properties (for example, water content, salinity) of the formation (Anderson, Adamson, and Stroo 2019), as well as the air-water interfacial affinity of individual PFAS (Brusseau 2019). In general, air-water interfacial partitioning can contribute to the bulk soil retention of PFAS in a manner that is unique among organic contaminants. Time scales required for PFOS (and other PFAS that exhibit strong interfacial adsorption characteristics) to reach the underlying groundwater have been simulated to be from 1 or 2 years to several decades or longer. The extent of this retardation factor will likely vary due to climate conditions and PFOS concentrations (Guo, Zeng, and Brusseau 2020; Brusseau 2020). This potential retardation could influence the selection and implementation of remedies, or even the duration of long-term management programs.

- Similar to the impact described above, retention within the vadose zone can occur because of the PFAS tendency to be associated with the air-filled pore space and (to a lesser extent) the solid phase, such that a limited portion of PFAS mass may be in the aqueous phase and subject to deeper infiltration (Guo, Zeng, and Brusseau 2020). Importantly, the interaction between solid phase sorption (hydrophobic partitioning and electrostatic interactions) and air-water interfacial partitioning could be important given that mass transfer limitations can create hysteretic desorption from soils with relatively high organic matter content (Schaefer et al. 2021).

Although some experimental and field-scale studies have reported PFAS transport by leaching (Lindstrom et al. 2011; Filipovic et al. 2015; Hellsing et al. 2016; Bräunig et al. 2017), others have observed long-term retention of longer chain PFAS on shallow soils after extended percolation (Sepulvado et al. 2011; Stahl et al. 2013; Anderson et al. 2016; Anderson 2021; Anderson et al. 2022). In a long-term lysimeter study using a silty soil with some clay and natural rainfall, PFOA and shorter chained PFCAs and PFSAs traveled more rapidly through the soil column than did PFOS (Stahl et al. 2013). However, even after 5 years, 96.88% and 99.98% of the mass of PFOA and PFOS, respectively, remained in the soil. This retention of PFOA and PFOS may increase the long-term persistence of the (soil-bound) source (Baduel, Paxman, and Mueller 2015). Due to the low (part per trillion) concentrations that are a concern in groundwater, slow leaching of PFAS from shallow soils may contribute to a persistent groundwater plume.

5.3.4 Transfer of PFAS between groundwater, surface water, porewater, and sediment

The interplay between PFAS and groundwater, porewater, surface water, and sediments is complex, and identifying the nature and implications of these interactions for PFAS fate and transport is very likely site-specific.

For example, studies within the Little Neshaminy watershed in southeastern Pennsylvania indicate instances where PFAS-containing groundwater impacts surface water and other instances where surface water PFAS concentrations may be diluted by groundwater discharge (Leidos 2019; Tetra Tech 2022). Field investigations have also demonstrated the migration of PFAS from groundwater to surface water via infiltration of groundwater to stormwater utilities (Leidos 2019; Wood 2020). Other investigations have indicated transport of PFAS from groundwater to surface water features such as marshland (Aerostar SES 2021). Investigations involving larger tributaries also indicate that migration of PFAS from groundwater to surface water may be impacted by seasonal and local variations in stream flow that may affect groundwater flow direction and gradients (Weston-ER Federal Services 2022).

A complete understanding of fate and transport implications of transfer of PFAS between surface water and groundwater requires an understanding of the differing conditions between surface water, groundwater, and the hyporheic zone.

Development of surface water quality standards for PFAS is discussed in Section 16. Information about PFAS occurrence in surface water and groundwater is included in Section 6.4 and Section 6.3, respectively and in Section 17.1. Additional case studies of PFAS transport between surface water and groundwater are discussed in Section 15.5.

5.3.4.1 Groundwater/Surface Water Interactions

Surface water and groundwater often have distinct chemistry or geochemistry, including differences in pH, ionic concentrations, dissolved oxygen, and sources and concentration of PFAS or other contaminants. Sediment porewater represents the boundary layer between groundwater and surface water where geochemical and redox transition zones may have significant fate implications for PFAS.

To date, there are very limited studies of PFAS at the surface water/groundwater boundary. One of the few published studies, Tokranov et al. (2021), looked at the PFAS concentrations, dissolved oxygen, and nutrients in downwelling of lake surface water. They found that precursor concentrations decreased from surface water to groundwater across the porewater boundary and attributed this decrease to biotransformation and sorption.

Redox gradients at the sediment porewater zone are expected to impact the fate of PFAA precursors (for example, from anoxic groundwater flow into surface waters). Reaeration of anoxic groundwater during exfiltration to surface water will lead to shifts in microbial populations, which in turn may alter transformation of PFAA precursors. An analogous process occurred when increased PFAAs were detected after biosparging in the field (McGuire et al. 2014) and in column studies (Nickerson et al. 2021; also see Section 5.4.4.2 and the case study in Section 15.1.1). This suggests groundwater/surface water redox transition zones have potential as hotspots for biotransformation. Additional abiotic transformations may also occur in anoxic groundwater to aerobic surface water boundaries.

There is limited information on how redox gradients impact PFAS sorption. However, aerobic transformation of PFAA precursors yields more mobile products (Weber et al. 2017), which in turn might be less likely to be adsorbed to solid phases. In addition to the impacts on precursor transformation, the perfluorocarbon chain length "head group, and a variety of environmental properties (for example, sediment organic carbon content, mineral and grain coating composition, pH, aqueous calcium and humic acid concentration) have all been shown to influence PFAS partitioning in laboratory experiments" (Tokranov et al. 2021). For example, Steffens et al. (2021) found that measured PFOS concentrations decreased significantly in ionic solutions due to an apparent "salting out" effect. The decrease in bulk solution PFOS concentrations with higher salinity was attributed to increased uptake of PFOS on the water-container interface, as well as increased aggregation at the air-water interface. The authors suggest that such an effect has implications on transport of PFAS in high-salinity environments or in areas where changes in salinity occur spatially or temporally, as increased salinity may lead to aggregation of PFAS on particulates, sediment, or other solids, as well as increased concentrations of PFAS in surface microlayers.

It is difficult to estimate the extent of PFAS introduction to surface waters from groundwater, especially when there are other surface point discharge sources, or transformation and sorption processes might significantly impact PFAS transport. However, Pétré et al. (2021) studied a site without direct outfalls of PFAS onto surface water and based on groundwater and surface water field measurements estimated up to 32 kg/yr for perfluoroether carboxylic acids (PFECAs) released from hyporheic exchange. Because of the high mobility and low retardation factor of PFECAs, the authors assumed low sorption and not enough time for transformation (days to months) assuming no transformation or sorption due to the low retardation factor of PFECAs. They indicated that adsorption would overestimate PFAS flux to surface water, and desorption would underestimate it.

5.3.4.2 Surface Water/Sediment Interactions

PFAS, particularly short chain PFAS, are mobile in the aquatic environment due to their high solubility in water (Ahrens 2011). This property further increases the difficulty of finding a correlation between concentrations in water, especially flowing water, and other media, such as sediments, fish, or invertebrates (Campo et al. 2016). A number of studies have sought to establish PFAS partitioning between surface water and sediments in lakes or other stationary water bodies, such as wetlands and estuaries (White et al. 2015; Mussabek et al. 2019; Bai and Son 2021; da Silva et al. 2022).

Occurrence of PFAS in sediments can be the result of transfer (partitioning) from the surface water column or deposition of PFAS sorbed to suspended solids. The relative contribution of each process in PFAS transport to sediments remains unclear as partition coefficients measured in the field are consistently higher than those measured in the laboratory (Zhang et al. 2015; Li, Oliver, and Kookana 2018; Rovero et al. 2021). Suspended solids originating from erosion of PFAS-impacted soil may contain much higher levels of PFAS compared to suspended solids with PFAS due to equilibrium deposition (Borthakur et al. 2021; Xiao et al. 2019). These suspended solids, eroded from PFAS-impacted soils, may mix with particulates present in rivers and streams through turbulent mixing and may lead to higher PFAS concentrations in sediment when the suspended solids settle.

Dated sediment core analysis allows estimation of deposition rates and fluxes of PFAS to surface water bodies. Studies in the Great Lakes suggest it may be effective for long-chain PFAS that exhibit greater sorption to sediment, with concentration at a given depth interval representing deposition during that time period. Short-chain PFAAs showed less sorption and were apparently more mobile in the sediment column, and therefore were not effective indicators of PFAS deposition rates. The authors (Codling et al. 2018) also noted that as more short-chain PFAS are used as replacements for PFAS applications, sediment cores may have less utility for evaluating trends in deposition rates. Age-dated sediment cores in a Swedish study (Mussabek et al. 2019) allowed estimation of deposition rates and fluxes of PFAS to ponds impacted by AFFF releases. The study identified peak deposition rates occurring between 2003 and 2009, which correlated with reported activity near the water bodies. The study noted that interpretation of fluxes must consider seasonal variations in water chemistry, sedimentation, and partitioning (Mussabek et al. 2019). Heavy precipitation or storm events can also contribute to episodic or enhanced transport of sediment and resuspension or redistribution of contamination in some environmental settings. Resampling of marine sediment locations in Florida following the passage of a hurricane found sediment concentrations of total PFAS decreased 47% averaged across nine sites (Ahmadireskety et al. 2021). Sediments can also influence surface water concentrations. Tributary sediments with a mix of potential sources were shown to be potential secondary sources of PFAAs once those sediments were transported to a receiving water body (Balgooyen and Remucal 2022).

Because PFAS concentrations in sediment may be the result of average deposition conditions of discharges that may be episodic, passive porewater samplers may be useful to characterize the surface water concentrations and correlate them with the sediment PFAS concentrations. Passive sampling provides an accumulation of contaminants and so generates a time-weighted mean concentration instead of a snapshot of concentration at a discrete time point. However, careful consideration must be given to the type of sampler, as equilibrium devices may not be appropriate for episodic discharges and accumulation devices could potentially represent the average concentrations in sediments. See Section 11.1.7 for more information about sampling environmental media.

In a recent study, PFBS, PFHxS, and PFOS in sediments collected from lake Sänksjön near Ronneby, Sweden, was found to be correlated to the sediment mineral content (Fe, Pb, Rb, and As) but not with the fraction of organic carbon (f_{oc}) based on principal component analysis (Mussabek et al. 2020). Other PFAS measured at the site (PFHxA, PFOA, and 6:2 FTS) had weaker associations with the mineral content. The sorption behavior of PFAS to sediments depends on both hydrophobicity and electrostatic interactions given the unique structure of PFAS with both polar and nonpolar moieties (Ahmadireskety et al. 2021; Lampert 2018). Sorption of PFAS to sediments is expected to be driven by similar variables as partitioning in soils. See Section 5.3.2 for additional discussion of factors driving partitioning and sorption. In aquatic environments and the hyporheic zone, sorption and desorption are likely to have direct effects on the mechanisms of PFAS transport (for example, transport in dissolved phase, retention due to sorption, or particulate transport due to sorption).

5.4 Transformations

5.4.1 Introduction

Numerous studies have reported both biotic and abiotic transformations of some polyfluorinated PFAS. Polyfluorinated PFAS shown to transform are referred to as *precursors* and typically form PFAAs. However, PFAAs have not been shown to degrade or otherwise transform under ambient environmental conditions. The fundamental differences between polyfluorinated precursors and perfluorinated chemicals that affect transformation potential are the presence, location, and number of carbon-hydrogen (C-H) bonds and *potentially* carbon-oxygen (C-O) bonds throughout the alkyl carbon chain. Specifically, PFAS with C-H bonds are subject to a variety of biotic and abiotic reactions that ultimately result in the formation of shorter chain PFAAs. Although available studies on both biotic and abiotic transformation of polyfluorinated PFAS primarily consist of controlled laboratory experiments (discussed below), an increasing number of field studies have also been published that demonstrate the relevance of precursors at a variety of sites with different source scenarios (for example, Weber et al. 2017; Dassuncao et al. 2017).

5.4.2 PFAA Precursors

Although PFAAs are limited to a fairly small number of homologous compounds that differ only with respect to carbon chain length and the terminal functional group, the number and diversity of polyfluorinated chemicals is vast. Thousands of PFAS are currently thought to exist (or have existed) on the global market, and the vast majority are polyfluorinated (Wang et al. 2017) (Section 2). However, transformation studies published to date are available for only of a small subsample of these PFAS, and therefore, much uncertainty exists regarding 1) the extent to which precursor transformation occurs on a global scale, 2) which environmental compartments represent the majority of transformation, 3) relevant environmental conditions that affect transformation processes, and 4) transformation rates and pathways. Nevertheless, the fraction of total PFAS that consists of PFAAs, both globally and (in particular) at contaminated sites, should be expected to increase due to transformation over time, over distance, and due to remediation, as depicted in Figure 5-3.

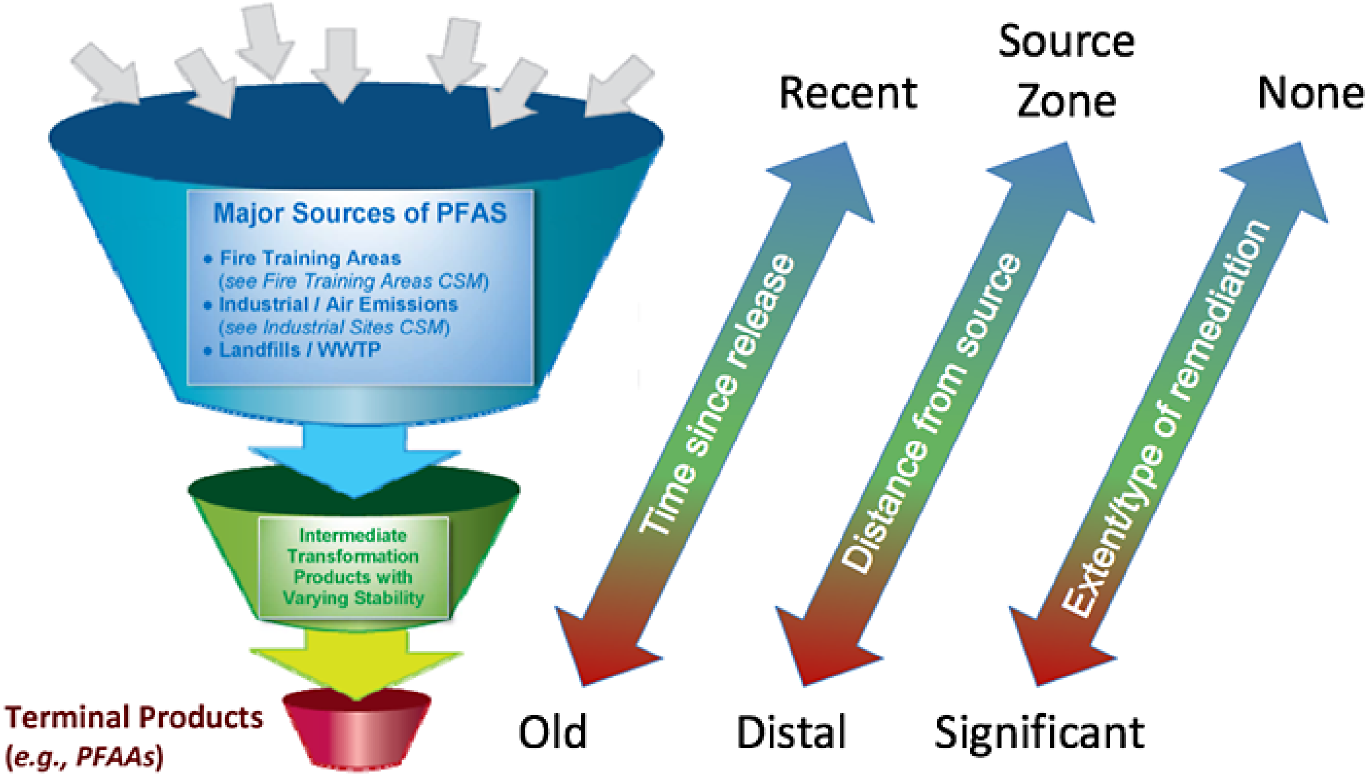


Figure 5-3. Illustration of precursor transformation resulting in the formation of PFAAs.

Source: L. Trozzolo, TRC, and C. Higgins, Colorado School of Mines. Used with permission and based on This Photo by Unknown Author is licensed under CC BY-SA.

5.4.3 Atmospheric Transformations

Although direct emission of PFCAs has declined globally, atmospheric emission of PFCA precursors has been increasing (Thackray and Selin 2017; Wang et al. 2014). Similarly, emission rates for PFSA precursors are increasing globally (Löfstedt Gilljam et al. 2016). Atmospheric transport is an important distribution mechanism for PFAS on both regional and global scales, which has led to documented PFAS occurrence (including PFAAs and PFAA precursors) in remote locations, including arctic regions (Young et al. 2007). Ocean currents also transports PFAS to arctic regions, although the relative contribution of each mechanism is not well understood (Yeung et al. 2017). Regardless of the relative contributions of atmospheric and oceanic transport, atmospheric transport and subsequent transformation of precursors has been documented as an important source of PFAAs in the environment (Young et al. 2007).

Widely measured PFCA precursors in the atmosphere include primarily FTOHs (Thackray and Selin 2017; Young and Mabury 2010; Martin et al. 2002). Wang et al. (2015) collected marine atmospheric samples during an expedition research cruise that spanned the Southern Ocean, Atlantic Ocean, and Arctic Ocean; samples were analyzed for several precursors, including FTOHs, FTAs, FOSAs, and FOSEs. The researchers found that FTOHs were the predominant species.

Atmospheric transformation of precursors, including FTOHs, may be an important source of PFCAs in the environment, such as those identified in the Arctic (Schenker et al. 2008). Although direct photolysis of PFAS has not been observed, indirect photolysis of some precursors does occur in the atmosphere and can be a significant contributor to PFCA deposition (Armitage, MacLeod, and Cousins 2009; Yarwood et al. 2007). For example, hydroxyl and chlorine radicals degrade 8:2 FTOH to PFOA in the atmosphere through reactions with hydroxyl and chlorine radicals, with similar reactions for 6:2 and 4:2 FTOHs (Ellis et al. 2004) and perfluoroalkyl sulfonamides, which may degrade to PFCAs and PFSAs (atmosphere) (Martin et al. 2006) and PFSAs (terrestrial environment) (Mejia Avendaño and Liu 2015). In addition to FTOH, other semivolatile precursors may also undergo atmospheric transformation to PFCAs (Young and Mabury 2010).

Atmospheric transformation of precursors to PFCAs is a multistep process, and the PFCA product yield is a function of several factors, including ratio of nitrous oxides (NO_x) and peroxy radicals (RO_2) species. High NO_x levels result in lower long-chain PFCA yields, thus long-chain PFCA yields are typically higher in remote regions (Young and Mabury 2010). Thackray and Selin (2017) calculated theoretical maximum yields for formation of PFOA and PFNA from 8:2 FTOH that were highly variable, ranging from far less than 1% to 40% (PFOA) or 80% (PFNA), depending on local photochemical conditions.

5.4.4 In Situ Transformations

5.4.4.1 Abiotic Pathways

Abiotic processes shown to cause transformations of precursors in soil and water under ambient environmental conditions include hydrolysis, photolysis, and oxidation. Hydrolysis of some precursors, followed by subsequent biotransformation, can produce PFSAs. An important example is the production of PFOS from perfluorooctane sulfonyl fluoride (POSF) (Martin et al. 2010). Other hydrolysis reactions produce PFCAs. In particular, Washington and Jenkins (2015) showed that the hydrolysis of fluorotelomer-derived polymeric precursors forms monomeric precursors of PFOA and other PFCAs with half-lives of 50–90 years at neutral pH. Also, oxidation of precursors by hydroxyl radicals can occur in natural waters, with the fluorotelomer-derived precursors being oxidized more rapidly than electrochemical fluorination (ECF)-derived precursors (Gauthier and Mabury 2005; Plumlee, McNeill, and Reinhard 2009). Shorter chain PFCAs as well as PFSAs such as perfluorobutane sulfonate (PFBS) also can be produced by oxidation reactions between hydroxyl radicals and sulfonamido derivatives (D'Eon et al. 2006). Finally, in some cases, abiotic precursor transformations may not initially produce any PFAA (for example, the formation of various polyfluorinated sulfonamido intermediate compounds from ECF-derived precursors), though eventual formation of PFAAs may still be possible.

5.4.4.2 Aerobic Biological Pathways

Evidence of aerobic biotransformation is provided from studies of PFAS composition throughout the continuum of wastewater treatment (see Arvaniti and Stasinakis (2015) for a comprehensive review), field studies at AFFF-impacted sites (for example, Houtz et al. 2013; McGuire et al. 2014; Anderson et al. 2016; Weber et al. 2017), and most authoritatively from microcosm experiments.

The literature on aerobic biotransformation collectively demonstrates, or indirectly supports, conclusions such as the following:

- Numerous aerobic biotransformation pathways exist with relatively rapid kinetics.
- All polyfluorinated precursors studied to date have the potential to aerobically biotransform to PFAAs.
- Aerobic biotransformation of various fluorotelomer-derived precursors *exclusively* results in the formation of PFCAs, including PFOA.
- Aerobic biotransformation of various ECF-derived precursors *primarily* results in the formation of PFSAs, including PFOS.

In detail, most commonly studied in microcosm experiments have been the 6:2 and 8:2 FTOHs in soil, sludge, or aqueous matrices. Although observed degradation rates and intermediates are variable among these studies, ≤ C8 PFCAs have been consistently observed as terminal transformation products (Dinglasan et al. 2004; Wang et al. 2005, 2005; Liu et al. 2007; Saez, de Voogt, and Parsons 2008; Wang et al. 2009). However, a pure culture experiment with *P. chrysosporium* (a white-rot fungus) reported much lower PFCA yields with alternate pathways (Tseng et al. 2014). Other telomer-derived polyfluorinated PFAS investigated include the 6:2 fluorotelomer mercapto alkylamido sulfonate (Weiner et al. 2013), the 6:2 fluorotelomer sulfonate (Wang et al. 2011), the 4:2, 6:2, and 8:2 fluorotelomer thioether amido sulfonates (Harding-Marjanovic et al. 2015), the perfluorooctane amido quaternary ammonium salt (Mejia-Avendaño et al. 2016), the 6:2 fluorotelomer sulfonamide alkylamine, and the 6:2 fluorotelomer sulfonamide alkylbetaine (D'Agostino and Mabury 2017). All demonstrate the formation of PFCAs with variable rates and inferred pathways. Aerobic biotransformation of various ECF-derived polyfluorinated PFAS has also been demonstrated in several studies. Studied PFSA precursors include N-ethyl perfluorooctane sulfonamido ethanol (Rhoads et al. 2008; Zhao et al. 2016; Zhang et al. 2017), N-ethyl perfluorooctane sulfonamide (Mejia Avendaño and Liu 2015), and perfluorooctane sulfonamide quaternary ammonium salt (Mejia-Avendaño et al. 2016). All demonstrate formation of PFSAs with variable rates and inferred pathways.

5.4.4.3 Anaerobic Biological Pathways

Few studies have been published to date conclusively demonstrating biotransformation of per- and polyfluorinated PFAS under anaerobic conditions. Different end-products of PFAA precursors have been observed between aerobic and anaerobic conditions (Choi et al. 2022). Aerobic, and to some extent, denitrifying conditions lead to PFAAs (Yi et al. 2022), but more reducing anaerobic conditions, such as iron- and sulfate-reducing, lead to other transformation products (Yi et al. 2018; Yan et al. 2022). FTOHs were studied in two instances, demonstrating the production of stable polyfluorinated acids under methanogenic conditions with much slower kinetics relative to aerobic biotransformation (Zhang et al. 2013; Allred et al. 2015). In a recent study, PFOA and PFOS were demonstrated to be defluorinated by a specific microbial strain (*Acidimicrobium sp*. Strain A6) under conditions where ammonium is oxidized while iron is reduced, a condition known as

Feammox (Huang and Jaffé 2019). The environmental significance of anaerobic biotransformations of polyfluorinated PFAS as sources of PFAAs is uncertain.

5.4.5 Polymer Transformation

Polymeric substances in the PFAS family include fluoropolymers, polymeric perfluoropolyethers, and side-chain fluorinated polymers (Buck et al. 2011). Detailed descriptions of these polymers appear in Section 2.2.2.1. Briefly,

- fluoropolymers are high–molecular weight solid plastics (> 100,000 Daltons, or Da according to Henry et al. (2018)) containing a carbon polymer backbone with fluorine directly attached to backbone carbon atoms.
- polymeric perfluoropolyethers contain an ether polymer backbone with F directly attached to carbon atoms. These polymeric PFAS are complex and mainly used as surfactants and surface protectants.
- side-chain fluorinated polymers contain a nonfluorinated polymeric backbone with fluorinated side chains; these are synthesized from telomer-derived precursors.

Polymer transformation research has indicated the following.

- Given the wide range of estimated half-lives, modeling assumptions for estimating the half-lives, different levels of residuals present in the polymer studied, highly variable molecular weights of the polymers studied with different surface area and size and with different extraction protocols, the polymer degradation studies are inconsistent.
- Other environmental conditions that need to be considered are redox, pH, temperature, percent moisture, and microbial activity in the soil microcosms for these long-term studies.
- Additional research is needed primarily on the biotransformation of side-chain fluorinated polymers, which are potential precursors to PFAAs.

Side-chain fluorinated polymers are widely used for many commercial and industrial applications as surfactant and surface-protecting products (Buck et al. 2011). Therefore, understanding the biotransformation potential of these polyfluorinated polymers is essential. However, few studies have reported on the potential biotransformation of side-chain polymers—for example, the fluorotelomer-based urethane polymer (Russell et al. 2010). Given the complexity of side-chain fluorinated polymers, there are many discrepancies among these studies. Primarily, the inability to monitor polymer concentrations is problematic. Because analytical methods for direct quantitation of polymers are not available, all the studies except Rankin et al. (2014) monitored suspected FTOH degradation products rather than the disappearance of the polymer (Wang et al. 2005; Liu et al. 2007; Wang et al. 2009; Dasu, Liu, and Lee 2012; Dasu and Lee 2016). Rankin et al. (2014) qualitatively monitored the disappearance of the polymer using matrix-assisted laser desorption/ionization time-of-flight (MALDI-TOF) mass spectrometry, in addition to monitoring known degradation products. Also, the presence of impurities or nonpolymerized residuals (monomers, oligomers, PFCAs, FTOHs, etc.) complicates data interpretation and potentially confounds conclusions on polymer biodegradation. Finally, the time frame for the biodegradability studies (max = 2 years) is much shorter than the extrapolated half-lives (decades to thousands of years) of these side-chain fluorinated polymers. Hence, modeling assumptions are also critical sources of variability.

Russell et al. (2008); Russell et al. (2010) investigated the biodegradation potential of two types of side-chain fluoropolymers, fluorotelomer-based acrylate polymer and urethane polymer in soils for 2 years. Based on the experimental data for PFOA, the estimated half-life of acrylate polymer was 1,200–1,700 years and of urethane polymer was 28–241 years (geometric mean of 102 years). However, the polymer used in this study contained high residuals. Later, Washington et al. (2009) studied the biodegradation potential of fluorotelomer-based polyacrylate, which contained low residuals, and based on the experimental data for PFOA, the acrylate polymer half-life was estimated at 870–1,400 years. Further, based on the assumption that degradation is surface-mediated, the authors also modeled and estimated the half-life for finely grained polymers, which are typical of commercial products. They did this by normalizing to the estimated surface area of the polymer and derived a half-life of 10-17 years, which suggests fine-grained, side-chain fluoropolymer products may be a potentially significant source of PFCAs to the environment. Washington et al. (2015) studied the biodegradability of commercial acrylate polymer for 376 days in soils using exhaustive extractions (Washington et al. 2014) and estimated half-lives ranging from 33 to 112 years. In this study, it was also observed that the acrylate polymer can undergo OH-mediated hydrolysis in pH 10 water and it degrades 10-fold faster than in the neutral treatment. This is the only abiotic transformation of side-chain fluorinated polymer reported in the literature, so the mechanism of abiotic degradation needs further investigation. Another research group, Rankin et al. (2014) studied the biodegradation of laboratory-synthesized fluorotelomer-based acrylate polymer in soil, plant, and biosolids for 5.5 months. Degradation rates were faster in plants and biosolids than in soils. Even in this study, a broad range of estimated half-lives of 8–111 years was reported. The modeling assumptions used in different studies lead to variability in reported half-lives (Russell et al. 2008; Russell et al. 2010; Washington et al. 2009, 2010, 2015, 2018).

5.4.6 Practical Implications

Precursor transformation can complicate CSMs (and risk assessments) and should be considered during comprehensive site investigations. For example, atmospheric emissions of volatile precursors can result in long-range transport where subsequent transformation and deposition can result in detectable levels of PFAAs in environmental media independent of obvious point sources (Vedagiri et al. 2018). Moreover, downgradient PFOA and PFOS groundwater concentrations, or downstream concentrations within treatment systems, can oftentimes be higher than near the source area/influent due to precursor transformation reactions such as oxidation. Also, PFOA and PFOS concentrations can exhibit an increasing trend over time as precursors transform with time and distance (Figure 5-3), which can influence the Remedial Investigation/Feasibility Study (RI/FS) scope and data evaluation.

With respect to site-related precursors, transformation of otherwise unmeasured PFAS into detectable PFAAs is obviously relevant to site investigations to the extent transformation occurs after initial site characterization efforts. Additionally, differential transport rates between precursor PFAS and the corresponding terminal PFAA could also confound CSMs if transformation rates are slower than transport rates, as has been suggested (Weber et al. 2017).

To account for otherwise unmeasurable precursors, several surrogate analytical methods have been developed, including the total oxidizable precursor (TOP) assay (Houtz and Sedlak 2012), particle-induced gamma-ray emission spectroscopy (PIGE) (Schaider et al. 2017), and adsorbable organic fluorine (AOF) followed by combustion ion chromatography (Wagner et al. 2013). For more information on these surrogate analytical methods to measure precursor concentrations, see Section 11.2.

5.5 PFAS Uptake into Aquatic Organisms

Some PFAS have a propensity to bioaccumulate. That is, they are taken up and accumulate in organisms from environmental media. Moreover, some PFAS may biomagnify up the food chain; for these compounds, lower levels of PFAS are observed in tissue from organisms at the base of the food chain and in lower trophic-level invertebrates and fish and higher tissue PFAS levels are observed in predatory fish and in air-breathing animals at the top of the food chain (for example, seagulls, polar bears) (Houde et al. 2011; Gobas, Kelly, and Kim 2020; Burkhard 2021). Trophic transfer of PFAS and biomagnification appear to be higher in air-breathing organisms (aquatic-dependent birds and mammals) than in gill-breathing species (for example, higher trophic-level fish species), presumably because the respiratory elimination of PFAS via gills to water is much greater than elimination from lungs to air (De Silva et al. 2021). It should be noted that not all PFAS biomagnify, and for some (for example, PFOS), the evidence regarding biomagnification is mixed (Franklin 2016).

The major mechanisms controlling aquatic bioaccumulation of PFAS are uptake (from water and food), depuration (which includes elimination across the gill surface, urine, and in feces) (Chen, Gong, and Kelly 2016; Zhong et al. 2019), growth dilution, and biotransformation. Within organisms, the extent of accumulation differs among types of tissues (for example, whole body, muscles, liver).

An understanding of bioaccumulation in field populations rests on evaluation of the following factors, which are common to PFAS, as well as to other contaminants:

- Exposure concentrations (concentrations of PFAS in sediments and water)
- Exposure to precursors
- Trophic level (higher trophic levels often exhibit higher concentrations)
- Movement and migration patterns, which determine the extent of exposure to contaminated areas that lie within the home range of an organism
- Bioenergetics (respiration rate, growth rate)
- Toxicokinetics (gut uptake efficiency, gill transfer efficiency, fecal elimination, biotransformation rate, differential protein binding)

Unlike nonionic polar organic compounds, which accumulate in fatty tissues, the bioaccumulation of ionic PFAS in aquatic biota is generally characterized as associated with proteins. Several studies (Jones et al. 2003; Han et al. 2003) reported that PFOS and PFOA are generally bound to serum albumin, as well as proteins in the liver and kidney, and differences among tissues in type of protein explain much of the PFAS variation among tissues (Ng and Hungerbuhler 2014, 2015). Binding to phospholipids is another mechanism for PFAS accumulation (Dassuncao et al. 2019). Thus, methods and models that characterize the bioaccumulation of nonionic polar compounds by assuming partitioning to lipids (using lipid normalization) are likely to be inappropriate for PFAS (see discussion of partitioning in Section 4.2.10).

Bioaccumulation of PFAS is generally characterized using three parameters:

- Bioconcentration factor (BCF)—the direct uptake of PFAS by an organism from the water column (for example, through the gills). This is measured in the laboratory. It is defined as the ratio of the concentration in an organism to that in the exposure water (typically in units of ng/kg wet weight / ng/L, or L/kg wet weight).
- Bioaccumulation factor (BAF)—the amount of PFAS taken up from water plus the contribution of PFAS in the diet of the organism. Both the organism and its diet are simultaneously exposed to the same exposure sources. This is generally measured in the field. The units are the same as for the BCF.
- Biomagnification factor (BMF)—the increase in tissue PFAS concentration moving up the food chain, based on a specific predator/prey relationship. The BMF is measured in the field and is typically reported in units of ng/kg wet weight in predator / ng/g wet weight in prey. The trophic magnification factor (TMF) similarly describes the increase in tissue PFAS concentration with trophic level, but it is estimated using data for multiple trophic levels. It is typically calculated as a regression of log(PFAS concentration) vs. trophic level, which is usually determined using the stable isotope 15N method (Franklin 2016).

BCFs, BAFs, and BMFs are used to understand the nature of bioaccumulation; for example, they are used in the European Union REACH designation of compounds as “bioaccumulative” in the Persistent, Bioaccumulative, and Toxic (PBT) and Very Persistent and Very Bioaccumulative (vPvB) assessments. They are also used to support risk assessments and in development of surface water quality criteria (see Section 16). Publications addressing PFAS BCFs, BAFs, BMFs/TMFs are too many and too broad to cover in this document. Several publications have reviewed PFAS bioaccumulation, including but not limited to Burkhard (2021); Houde et al. (2006); Houde et al. (2011); Martin et al. (2013); Conder et al. (2020); Gobas, Kelly, and Kim (2020); and De Silva et al. (2021).

To support better understanding of PFAS bioaccumulation in aquatic species, available BCF and BAF data are provided in Table 5-1 (as a separate Excel file). BCF and BAF values for both invertebrates and fish are included. PFOS is the compound for which BCFs and BAFs are most commonly reported. This is expected because it is generally the most abundant PFAS in the tissues of aquatic organisms. The Table 5-1 Excel file consists of two sheets, the Database that reports values found in relevant literature and a Log sheet that lists each reference that was reviewed.

Table 5-1 includes BCF or BAF values reported in published studies that were compiled as of September 2021. All of the BCF studies were performed in the laboratory under controlled conditions, while the BAF studies were performed in the field. All studies were subject to quality review, which was performed in a qualitative manner. First, the table includes only BCF and BAF values that were reported in the publications. In some studies, PFAS concentrations were measured in water and biota, but BCF or BAF values were not reported. In such studies, BCF or BAF values may not have been reported due to several potential factors—for example, proper spatial and temporal matching of the data. In light of such uncertainties, BCF or BAF values were not calculated for the table. These studies are noted in the Log sheet, for the user’s consideration.

In addition, a number of studies were reviewed but not included in the Database sheet for various reasons; these studies are also indicated in the Log sheet (column “BAFs or BCFs presented in Table 5-1?”), and notes on each study are provided in the column “Comment.” A quantitative ranking was not conducted, along the lines of Burkhard (2021), who developed a parallel and largely overlapping database of BAF values and classified each study into one of three data quality categories based on several factors (number of fish and water samples, temporal and spatial coordination between the water and fish sampling, and general experimental design). Burkhard (2021) concluded that “The distributions suggest that there are not big differences across the three measurement quality rankings.” This suggests that the lack of a quantitative quality review of each study in Table 5-1, along the lines provided by Burkhard (2021), is not likely to be a significant limitation to the usefulness of the information. Additional information is provided in the README sheet of the Table 5-1 Excel file.

Information on best practices for conducting laboratory bioaccumulation tests is provided by OECD (2012), USEPA (2016), and ASTM (2013). Information is also available concerning the design and interpretation of field and laboratory BAF studies (for example, Burkhard 2003; Gobas et al. 2020). These resources may be useful in guiding the interpretation of the studies included in the database.

The following sections provide overviews of the available PFAS bioaccumulation data.

5.5.1 Bioconcentration

Table 5-1 presents available BCFs for several PFAS. Variation in the reported values is observed in the BCFs and is related to the specific PFAS, exposed species, tissue type, and other factors.

Studies have indicated that chemical structure, particularly the length of perfluoroalkyl chain and the presence of functional groups (carboxylate vs. sulfonate), influence their bioaccumulation potential. Martin et al. (2003) exposed rainbow trout to individual PFAS for 12 days. The PFAS with shorter perfluoroalkyl carbon chain lengths (< 7 for carboxylates and < 6 for sulfonates) had negligible BCFs. At 8–12 carbon chain length, uptake of PFAS compounds was proportional to the carbon chain length and inversely proportional to the critical micelle concentration (CMC; the concentration at which one half of the molecules are associated as micelles). Others have also shown that shorter chain PFCAs and PFSAs (less than eight and six carbons, respectively) are not readily bioconcentrated or accumulated (Conder et al. 2008; Martin et al. 2013; Houde et al. 2011).

Martin et al. (2003) also showed that PFSAs had greater BCFs and half-lives than the corresponding PFCAs of equal chain length, indicating that hydrophobicity, as predicted by the CMC, is not the only determinant of PFAS bioaccumulation potential and that the functional group must be considered.

With respect to tissue types, Martin et al. (2003) showed that PFAS accumulated to the greatest extent in the blood, followed by the kidney, liver, and gall bladder. Lower levels accumulated in the gonads, followed by adipose tissue and muscle tissue. This tissue-dependent distribution has been shown in many other studies and is apparently due to PFAS having a high affinity for serum albumin and fatty acid–binding proteins (Ng and Hungerbuhler 2014, as well as to binding to phospholipids (Dassuncao et al. 2019).

5.5.2 Bioaccumulation

Table 5-1 presents available BAF data for several PFAS. As shown, BAFs may be reported using concentrations measured in whole bodies or specific tissues. BAFs reported for fish muscle or fillet are useful for human health risk assessments (for fish consumption) and for developing corresponding water quality criteria (see Section 16). Whole-body BAFs can be used in ecological risk assessments for higher trophic organisms (for example, predatory fish, piscivorous birds and mammals) and developing corresponding water quality criteria. However, Conder et al. (2020) proposed using lab-derived BCFs instead of field-based BAFs in ecological risk assessments, primarily because lab-based BCFs are less variable and generally more reliable than field-based BAFs. Furthermore, PFAS associated with freshly spiked laboratory media may be more bioavailable than in the field, potentially leading to conservative BCFs (higher than what would occur under field conditions). Field-based BAFs may be affected by the presence of precursors (Langberg et al. 2020), making risk assessments and water quality criteria based on these BAF estimates unreliable. However, site specificity of field-based BAFs may be important to consider in specific situations, such as in the refinement of site-specific risk assessments and development of site-specific water quality criteria.

When comparing BAFs among organisms, or when developing statistical summaries of BAF values, differences among tissues in the extent of accumulation must be considered. The approach that is simplest, and which probably provides the most robust approach to comparisons of BAFs among organisms, is to report BAF values on a whole-body basis, since tissue-specific BAFs may vary among species due to differences in toxicokinetics. Such data may be collected using either whole-body samples or tissue-specific measurements that can be mathematically combined to yield equivalent whole-body concentrations. In aquatic organisms, PFAS concentrations in muscle are generally within a factor of two of whole-body concentrations (Goeritz et al. 2013; Shi et al. 2015).

Bioaccumulation of some PFAS has been observed in a variety of wildlife, generally fish-eating species, across the globe as demonstrated by the large number of studies reporting wildlife PFAS residues. Bioaccumulation data are now available for a wide range of environments, including water bodies directly adjacent to or downstream of manufacturers of PFAS, industries that use PFAS in manufacturing processes, firefighting, and wastewater treatment plants, as well as urban areas and areas distant from specific sources (De Silva et al. 2021). The majority of sampling has been conducted to support risk assessments and fish consumption advisories, as well as hypotheses concerning long-range fate and transport, temporal trends, and the identification of sources. Most of the work has been performed in the Northern Hemisphere, and some authors have found that levels are lower in the Southern Hemisphere (Armitage et al. 2009; Ahrens et al. 2009; Ahrens 2011; Benskin et al. 2012). One study in Australia, however, found among the highest PFOS concentrations reported worldwide in the livers of dolphins in heavily industrialized regions of South Australia (Gaylard 2017).

Some insights regarding PFAS bioaccumulation of PFCAs, PFSAs, and precursors are as follows:

- Similar to bioconcentration, bioaccumulation of PFAAs depends on carbon chain length (Brendel et al. 2018]). USEPA (2017) considers PFCAs with less than seven perfluorinated carbons (PFCAs shorter than PFOA) and PFSAs with less than six (such as PFBS) to less bioaccumulative. PFSAs are more bioaccumulative than PFCAs of the same carbon chain length.
- Bioaccumulation and biomagnification factors measured in the field vary widely (Franklin 2016; Gobas, Kelly, and Kim 2020; Burkhard 2021). Some PFAAs exhibit BAFs that overlap the range often used as criteria for bioaccumulation, for example by USEPA, Canada, and the European Union (1,000–5,000 L/kg).

Available BAFs in Table 5-1 validate some of the above insights. For example, in comparing BAFs for PFOA with PFOS across all species, it is clear that the BAFs for PFOA are much lower than PFOS. Moreover, comprehensive reviews (Ahrens and Bundshuh 2014; Houde et al. 2008) indicate that PFOS (8-carbon chain PFSA) is typically the most common PFAS observed in fish, as well as air-breathing animals, although in invertebrates, PFOA and PFOS can exhibit similar concentrations (~1–10 ug/kg). Ahrens and Bundshuh (2014) attributed the lower bioaccumulation of PFOA than PFOS to shorter chain (7 perfluorinated carbons in PFOA vs. 8 perfluorinated carbons in PFOS). Overall, the data in Table 5-1 indicate that for perfluorocarboxylates, BAFs increase until 11 or 12 perfluorinated carbons and decline for larger compounds.

Finally, it is important to note that PFAS precursors may contribute to the PFAS body burden. Asher et al. (2012) and Langberg et al. (2020) provided field data indicating an important contribution from precursors to PFOS concentrations in organisms via internal transformation. In addition, atmospheric measurements have shown the widespread occurrence of PFAS precursors like FTOHs and perfluorinated sulfonamide alcohols. Once absorbed by an organism, the precursor(s) may be metabolized to PFOA (for example, from 8:2 fluorotelomer alcohol) or to PFOS (for example, from N-ethyl perfluorooctane sulfonamidoethanol) (Gebbink, Berger, and Cousins 2015; Galatius et al. 2013). Additional research on how PFAS precursors may contribute their bioaccumulation in fish and wildlife is needed.

5.5.3 Biomagnification

Biomagnification factors may be used in the regulatory determination of whether contaminants biomagnify up the food chain and in food web modeling in risk assessments. Key conclusions from published literature are summarized in this section.

Studies of PFAS in the Great Lakes and marine/arctic ecosystems have generally shown that there can be trophic-level biomagnification within a food web, particularly for PFOS and some long-chain PFCAs (Martin et al. 2004; Houde et al. 2006; Houde et al. 2011; Butt et al. 2010; Tomy et al. 2004, 2009).

Martin et al. (2010) estimated BMFs for a pelagic food web in Lake Ontario, with the lake trout as the top predator. They were able to show, after adjusting for benthic versus pelagic organisms, that some PFAS compounds biomagnify, with TMFs ranging from 0.51 for FOSA to 5.88 for PFOS.

A study by Houde et al. (2006) looked at PFOS and C8–C14 perfluorinated carboxylates in the bottlenose dolphin at two marine sites (Sarasota Bay, FL, and Charleston, SC). Based on estimated TMFs, those authors concluded that PFOS and C8–C11 PFCAs biomagnified in this marine food web (Table 5-1, also cited by (Franklin 2016)). Interestingly, for PFCAs, PFOA had the highest TMF, with values progressively decreasing as chain length increased. Conder et al. (2008) reported similar results for perfluorinated acids, with BMF values ranging from 0.1 to 20 (geometric mean of 2). They concluded and Lescord et al. (2015) affirmed that PFCAs with less than seven carbons, and PFSAs with less than six carbons, do not biomagnify and that the bioaccumulation of PFCAs can be directly related to fluorinated carbon chain length (just as the bioaccumulation of persistent lipophilic compounds can be related to hydrophobicity). Conder et al. (2008) also noted that the biomagnification of PFCAs in aquatic food webs is lower than that of most persistent lipophilic compounds, with PFOS being the only perfluorinated acid consistently exhibiting the potential for biomagnification. Finally, Butt et al. (2008) observed biomagnification factors for PFAS in “ringed seal–polar bear” food webs of the Canadian Arctic. Biomagnification factors were greater than one for C8–C14 PFCAs, as well as for PFOS and PFOSA. Like Houde et al. (2006), they observed a decrease in BMF as the carbon chain number increased.

Contrary to other freshwater studies, Lescord et al. (2015) did not find evidence for biomagnification in total PFAS, total PFCA, total PFSA, and PFOS. These authors observed negative relationships between trophic level, as measured using stable nitrogen isotope ratios (δ15N), and concentrations of the studied PFAS compounds (PFOS, total PFCA, total PFSA, and total PFAS) in several of the six lakes, suggesting no biomagnification in these freshwater arctic food webs. Overall, their results suggested that a taxon’s horizontal but not vertical position in the food web affects its PFAS concentrations.

Because the BMF or TMF is the concentration in a predator divided by the concentration in its prey, calculated BMFs can be highly variable depending on what types of tissues were analyzed and what assumptions the researcher made in defining biomagnification relative to the animals' prey diet (often determined through analysis of stomach contents). Franklin (2016) analyzed the results of 24 peer-reviewed studies reporting field-derived BMFs or TMFs for 14 PFAS. BMF values ranged over several orders of magnitude, from 0.01 to 373 (including only nonzero values). TMFs varied from 0.1 to 20 (including only nonzero values). Franklin (2016) attributed this variability to several factors, including differing ways in which the metrics are expressed (for example, individual tissue analyses versus whole body), nonachievement of the assumed steady-state conditions, uncertainties in feeding ecology, and the metabolism of precursor compounds.

5.5.4 Characterization of Bioaccumulation in Criteria Development and Risk Assessments

In regulatory contexts, BMFs may be used to determine whether or not contaminants are considered bioaccumulative: a BMF greater than 1 indicates that a contaminant is bioaccumulative. The relationship between the BAF and BCF also provides relevant evidence.

Because consensus has not been reached regarding the extent of bioaccumulation and/or biomagnification of some PFAS, most importantly PFOS, the best approach to determining bioaccumulative status of PFAS and to conducting risk assessments is an active subject of discussion (Franklin 2016; Conder et al. 2020). Franklin (2016) made the case that "in practice, the study-to-study (and even within-study) variability of the results is so great that [field-measured BMFs and TMFs] are of very restricted usefulness for assessing bioaccumulation potential status." Franklin (2016) proposed basing the bioaccumulative status of a compound only on laboratory BCFs and on measurements of BMFs conducted under strictly monitored conditions, rather than relying on field-measured BMFs or TMFs. For fish, studies can make use of the OECD 305 protocol (OECD 2012). For terrestrial and avian species, dietary BMF determinations can be performed using laboratory rodents or cows or pigs fed with naturally contaminated feed, as well as avian species.

Similarly, Conder et al. (2020) proposed using laboratory-derived BCFs instead of field-based BAFs in ecological risk assessments, because lab-based BCFs may be less variable and generally more reliable than field-based BAFs. Moreover, lab-based BCFs are expected to provide conservative estimates of bioaccumulation, as PFAS may be more available in freshly spiked environmental media compared to aged PFAS in field samples. Furthermore, Conder et al. (2020) argued that laboratory BCFs avoid complications with the presence of PFAS precursors, which may transform into stable PFAS in field samples.

However, laboratory BCFs (studies in which organisms are exposed to contaminant in the water only) are subject to methodological limitations—for example, for substances that are highly sorptive. Furthermore, laboratory BCFs do not account for biomagnification, and for this reason will tend to provide low estimates of true BAFs. An approach similar to that proposed by Franklin (2016), namely, combining laboratory-measured BCFs with BMFs measured under controlled conditions, may be reasonable.

Furthermore, while avoiding the complications of precursors, laboratory BCFs also do not account for the contributions of precursors to tissue concentrations of PFOS. PFOS BAFs measured by Langberg et al. (2020) were the highest in Table 5-1, ranging up to about 250,000 L/kg wet weight muscle for PFOS in yellow perch. This value far exceeds values that have been measured in other sites, generally in the range of 1,000–10,000 (Table 5-1). This high value was attributed to the primary role of precursors in determining organisms' tissue concentrations of PFOS at this site. In an ecological risk assessment for such a site, a tissue concentration determined using measured water column PFOS concentrations and a laboratory-derived BCF (on average, on the order of approximately 1,000 L/kg wet weight whole body for PFOS) would significantly underestimate the true tissue concentration. Thus, if tissue concentrations are primarily determined by precursor levels in the system, then measurement of the substance in water is not appropriate in the first place. Rather, the organism exposure to the precursor(s) itself needs to be measured.

Gobas, Kelly, and Kim (2020) proposed that the bioaccumulative nature of compounds can best be evaluated by focusing on the BMF as measured using dietary-based OECD 305 studies (OECD 2012) , interpreted using a two-compartment bioaccumulation model to estimate the BCF and the BAF. The domain of applicability of the model developed by Gobas, Kelly, and Kim (2020) was limited to nonionic organic chemicals, and so would have to be modified for application to PFAS.

Bioaccumulation rates may differ between linear and branched isomers of PFAS (Conder et al. 2020), and it is hypothesized that linear PFAS are more bioaccumulative than branched PFAS (Houde et al. 2008, 2011). The use of more bioaccumulative isomers in laboratory BCF studies would result in a conservative, but potentially unrealistic, risk assessment for a field population exposed to a mixture of isomers. A full evaluation of the impact of isomer composition will require evaluation of the extent to which differences in bioaccumulation are significant, as well as the relative abundances of isomers in the environment.

Thus, in determining bioaccumulative status and in conducting risk assessments, the variability of field-measured BAFs and BMFs must be balanced against the biases and limitations associated with laboratory BCFs and BMFs. Such evaluations must be performed on a compound-specific basis, taking into account the confounding role of precursors. It is likely that a weight of evidence approach will be called for, given the uncertainties associated with PFAS bioaccumulation.

5.6 PFAS Uptake into Plants

Because PFAS contain a hydrophilic functional group, plants can be expected to take some of these compounds up through their root systems, after which they would be translocated to stems, shoots, leaves, and fruiting bodies. Plants growing closer to contaminated sources or irrigated with PFAS-containing water would be expected to accumulate higher concentrations of PFAS compared to plants more distant from the PFAS source (Gobelius, Lewis, and Ahrens 2017), subject to site-specific conditions such as soil properties. It has already been documented that the land application of biosolids may contaminate soil with PFAS and that animals fed silage from land-applied fields can have elevated concentrations of PFAS in their tissues (Lindstrom et al. 2011; Skutlarek, Exner, and Farber 2006). This also raises concerns about contamination of wildlife consuming plants from agricultural areas. Airborne PFAS emissions from industrial sites in China were found to impact the concentration of PFAS in bark and tree leaves, with the theory that bioconcentration in the latter may occur through the stomata (Shan et al. 2014).

Understanding uptake of PFAS into plants is critical in evaluating the fate of PFAS among various environmental compartments, particularly along the food chains with implications for human and ecological exposures to PFAS. Human exposure may occur via consumption of PFAS-impacted produce and dairy and meat products from animals fed with PFAS-impacted plant-based feed. Potential wildlife exposure to PFAS may occur via PFAS taken up in plants at impacted sites and releases.

The following sections provide an overview of PFAS uptake pathways and mechanisms in plants and bioconcentration/bioaccumulation

5.6.1 Uptake Pathways

Wang et al. (2020) provides an extensive review of uptake and accumulation of PFAS in plants. That study forms the basis of the overview provided in this section. As described in Wang et al. (2020), uptake of PFAS has been well documented in different native and planted species to varying degrees. The majority of these studies have focused on PFOA and/or PFOS uptake by agricultural crops, although there are many other PFAS that have been shown to be subject to plant uptake. Wang et al. (2020) also reported that while most published studies were conducted under controlled lab conditions, at least 16 field studies were identified. These field studies typically have focused on point sources of PFAS, including manufacturing sites, fire training areas, wastewater treatment plants, or landfills.

PFAS may be introduced to plants from soil, water, or air by:

- irrigation with impacted water
- land application of biosolids
- leachates from landfills
- impacts or releases at PFAS sites
- emissions and atmospheric deposition

Plant uptake is both PFAS- and soil-specific. PFAS with higher aqueous solubilities/diffusivities with less soil/air-water interface (AWI) retention affinity are often observed with greater uptake potential (bioavailability). For example, Wang et al. (2020) compiled bioconcentration factors (BCFs) for different PFAS that had been reported in literature studies; the bioconcentration factor is the ratio of the PFAS concentration in the plant tissue to the concentration in the soil. This compilation showed the median BCF values for PFBA and other short-chain PFAS were generally more than an order of magnitude greater than the values for long-chain PFAS like PFOA and PFOS. These patterns confirm that the physical-chemical properties of PFAS influence the extent of plant uptake. Likewise, physical-chemical soil properties (for example, organic matter content and composition, pH, salinity, temperature) affect plant uptake of PFAS, although this has not been comprehensively studied. Also, plant species and physiology (for example, transpiration rate and protein content) are important factors as discussed below.

PFAS accumulation in plants occurs primarily via root uptake from soil and water (Stahl et al. 2009; Lee et al. 2014; Wen et al. 2013; Zhang et al. 2019). Aerial uptake of PFAS from the ambient environment (vapor-phase and particle-bound) have also been reported, such as into leaves and bark (Stahl et al. 2014; Jin et al. 2018; Tian et al. 2018; Liu et al. 2019). However, aerial uptake contributes minimally to overall PFAS accumulation in plants (Wang et al. 2020).

As noted above, availability of PFAS in soil porewater for root uptake is largely dependent on the aqueous solubility of specific PFAS (see Section 4) and controlled by interactions with the soil phases and the AWI (see Section 5.2.3). PFAS in soil porewater migrates toward plant roots by transpiration and diffusion resulting from a local concentration gradient (Lechner and Knapp 2011). Recent studies by Zhang et al. (2019) and Wen et al. (2013) indicate a concentration-dependent process in root uptake that is mediated by transport proteins in cell membranes such as aquaporins and anion channels. PFAS enter the vascular tissue after passing through the root epidermis, cortex, and endodermis via apoplastic and symplastic pathways (Blaine et al. 2013).

Once in the root xylem, PFAS are translocated to different parts of a plant, such as stem, shoots, leaves, fruits, and grains. The degree of PFAS translocation in these tissues appears to depend on the transpiration stream, with more PFAS accumulation occurring in parts with greater capacity for sorption or incorporation and receiving greater amounts of water (Krippner et al. 2015; Lechner and Knapp 2011; Gobelius, Lewis, and Ahrens 2017; Stahl et al. 2009). For example, in carrots, cucumbers, and potatoes grown in soil mixed with PFAS-contaminated sewage sludge, Lechner and Knapp (2011) found less PFOA and PFOS accumulation in peeled edible parts than in foliage, leaves and stalks., Stahl et al. (2009) found much higher PFOA and PFOS in grains than in straw of spring wheat, oat, and maize. In trees, Gobelius, Lewis, and Ahrens (2017) evaluated the distribution of PFAS at an AFFF release site and reported that total PFAS accumulation followed leaves > twigs > trunk/core or roots in birch and spruce.

5.6.2 Bioconcentration/Bioaccumulation

Table 5-2 (provided as a separate Excel file) contains BCF and BAF values for 14 different PFAS for a variety of plant species. In the cited plant uptake studies, BCF and BAF are defined as PFAS concentration in plant (mass/mass) divided by PFAS concentration in soil (mass/mass) and are used interchangeably. This differs from the definition of BCF and BAF for animals in Section 5.5. A number of BAF values were obtained from studies in which PFAS was introduced to crops through irrigation water or biosolids-amended soils (Blaine et al. 2013, 2014, 2014). The materials harvested for analysis included both inedible (for example, plant leaves) and edible portions of crops (fruit, lettuce leaves, and roots). Other BCFs and BAFs were obtained from investigations of plants exposed to PFAS from soil, groundwater, surface water, or air in close proximity to PFAS release sites (Mudumbi et al. 2014; Zhang et al. 2015; Gobelius, Lewis, and Ahrens 2017). In general, it can be observed that 1) the shorter chain (more water soluble) PFAS are taken up more readily than the longer chain homologues, and 2) the majority of the plant BCFs and BAFs fall between a range of 0.1 and 10. A BCF or BAF of 1.0 indicates no net accumulation of PFAS from soil to plant. Such a BCF or BAF indicates that the soils and the plant of interest have the same concentration of PFAS per unit weight. This, however, does not indicate that an equilibrium condition exists between soils and plants. Some plants, like lettuce, contain a large percentage of water, which may help to explain the relatively high BAF of 56.8 observed by Blaine et al. (2013). In the controlled studies of edible crops, short-chain PFCAs and PFSAs exhibited greater BAFs compared to long-chain compounds.

Blaine et al. (2013) studied the uptake of PFAAs by greenhouse lettuce and tomato grown in soils prepared to mimic an industrially impacted biosolids-amended soil, a municipal biosolids-amended soil, and a control soil (but incorporated contaminated biosolids equivalent to 10 times higher than the agronomic rates allowed for Class B biosolids), a municipal biosolids-amended soil, and a control soil. BCFs for many PFAAs were well above unity, with PFBA having the highest BCF in lettuce (56.8) and PFPeA the highest in tomato (17.1) in the industrially impacted biosolids-amended soil. BAFs for PFCAs and PFSAs were, in general, slightly higher in the industrially impacted soil than in the municipal soil (~0.3−0.8 log units). The BCFs for PFAAs in greenhouse lettuce decreased approximately 0.3 log units per -CF_2 group (one carbon, two fluorine groups in a molecule). They also conducted a limited field study, in which they measured PFAA levels in lettuce and tomato grown in field soil amended with only a single application of biosolids (at the agronomic rate for nitrogen). The PFAA levels were predominantly below the limit of quantitation (LOQ). In addition, corn stover, corn grains, and soil were collected from several full-scale biosolids-amended farm fields. At these fields, all PFAAs were below the LOQ in the corn grains and only trace amounts of PFBA and PFPeA were detected in the corn stover. The Blaine et al. (2013) study confirms that the bioconcentration of PFAAs from biosolids-amended soils depends strongly on PFAA concentrations, soil properties, type of crop, and analyte. BCFs developed in Blaine et al. (2013) can be seen in Table 5-2.

Ghisi, Vamerali, and Manzetti (2019) provided a review of PFAS uptake in agricultural plants, including the potential for uptake from groundwater, soil, and air. Factors contributing to plant uptake include PFAS chain length, functional group, plant species, growth media, soil organic matter, and other soil properties. In general, higher PFAS concentrations in soil are correlated with higher PFAS concentrations in plants; however, the increase in concentrations may not be directly proportional. Short-chain compounds tend to accumulate at higher concentrations in leafy vegetables and fruits, whereas long-chain compounds tend to accumulate more in roots. Several studies have found that PFCAs accumulate at higher rates than PFSAs. Soil organic matter has been found to sequester PFAS and limit plant uptake in some studies reviewed. Another review of bioaccumulation factors for agricultural plants is Lesmeister et al. (2021).

Gobelius, Lewis, and Ahrens (2017) studied the uptake of 26 PFAS in plants (trees) at an AFFF (fire training) site with contaminated soil and groundwater. Samples from groundwater and different plant species (birch, spruce, cherry, ash, elder, beechfern, and wild strawberry) and tissues (that is, roots, trunk/cores, twigs, leaves/needles) were collected. Foliage had the highest BCFs of all tissues, ranging from 0 to 14,000 and accumulated the highest number ofPFAS (8 out of 26), with birch sap showing BCF values up to 41 for 6:2 FTSA. The highest mean BCFs were found for 6:2 FTSA (472; n = 52), PFOS (28; n = 36), PFHxS (10; n = 42), and PFOA (5; n = 24), which might correspond to the AFFF composition used at the site. For PFOA, the mean BCFs (±s.d.) were 18 ± 15 for spruce, followed by birch (1.2 ± 1.5) and cherry (0.25 ± 0.043). The authors concluded that PFAS were detected in all plant species, and the distribution followed the order of “shoots to roots”—that is, leaves > twigs/stems > trunk > roots. They cited other authors who have shown that “this order has proven applicable to all samples and species.” Hence, PFAS tend to accumulate in the vegetative portions rather than in the plant storage tissues.

Updated September 2023.

6 Media-Specific Occurrence

The long period of time during which PFAS have been produced and the many sources of PFAS release to the environment have resulted in low-level contamination of most environmental media worldwide. The concentrations of these human-caused ambient or "anthropogenic background" concentrations may vary widely, based on proximity to industrial areas, patterns of air and water dispersion, and many other factors. As a result, any claims regarding "universal" values for anthropogenic background levels of PFAS should be viewed skeptically.

This section provides a relative understanding of PFAS concentrations in various environmental media but does not represent an exhaustive literature review. These figures and summaries are intended to provide context to the reader and a starting point for further study. Media-specific occurrences of PFAS are constantly being added in the literature and on state, federal, and other countries' PFAS websites. USEPA has developed an online database called the PFAS Analytic Tools that provides access to different sources of information about potential PFAS sources, drinking water sampling data, occurrence in environmental media, and other types of information (USEPA 2023).

The following sections include figures summarizing the observed concentrations of PFAS that have been reported in the recent literature (approximately 2017–2022) and new information to date on the occurrence of PFAS in media that were not included in the previous version of this guidance document for outdoor air, indoor air, precipitation, dust, soil, sediment and biosolids. The figures for ground water and surface water were updated with the new format, but the data are from the previous summary. The previous version of this section (June 2022) is archived as a PDF under Archived External Tables and Sections on the home page of this site. Figure 6-5, Observed PFAS concentrations in fish, has not been updated.

Tables (linked as PDFs) that include important details concerning the studies used in developing the figures below and interactive versions of the figures (linked as a web page) are in Section 17.1. The figures were developed using R software and the static figures were developed using ggplot2 (Wickham 2016). Media-specific occurrence information that was included in the previous version of this guidance document (June 2022) is archived as a Section 17.1 PDF, found under Archived External Tables and Sections on the home page of this site.

As discussed in Section 2.6, the presence of some PFAS in environmental media and ecological receptors has been traced to the migration of PFAS in air emissions and through the direct discharges to soil, groundwater, and surface water. Sections on Phase Partitioning (Section 5.2) and Media-Specific Migration Processes (Section 5.3) illustrate that PFAS occurrence in the air, aqueous, and solid phases is highly interrelated. Sections on Human Health Effects (Section 7.1) and Ecological Toxicology (Section 7.2) suggest that PFAS risks to human health may result from exposure via drinking water, groundwater, soils, food, and other media types. Further, ecological impacts are widely observed. This suggests that a complete assessment of PFAS sources and exposure risks, including fate and transport processes that may drive future exposure concerns, requires understanding of PFAS occurrence across multiple phases. The processes that influence media-specific PFAS concentrations are illustrated in CSMs shown in Figure 2-20, Figure 2-21, and Figure 2-22. This section focuses on occurrence in air; soil, sediment, and biosolids; groundwater; surface water; and biota.

Environmental PFAS occurrence is an area of active research. As discussed in Section 11, sampling and analytical methods are still being optimized and standardized, and vary between studies. Data-reporting formats also vary, often including the observed minimum, maximum, or percentiles to represent the range, and arithmetic mean, geometric mean, or median values to represent central tendency. In some cases, only the average or maximum values are reported. Studies also vary in terms of research objectives and site characteristics, focusing on relatively pristine (for example, rural) or impacted (for example, industrial) sites. Some studies focus on certain PFAS, Finally, variable method detection limits between studies introduces the potential for non-detect data to impose artificial patterns. Due to these data limitations, the ranges and averages of detected PFAS concentrations presented in the following figures should be considered as a general frame of reference, rather than precise, dispositive thresholds.

Section Number	Topic

6.1	Air
6.2	Soil, Sediment, and Biosolids
6.3	Groundwater
6.4	Surface Water
6.5	Biota

6.1 Air

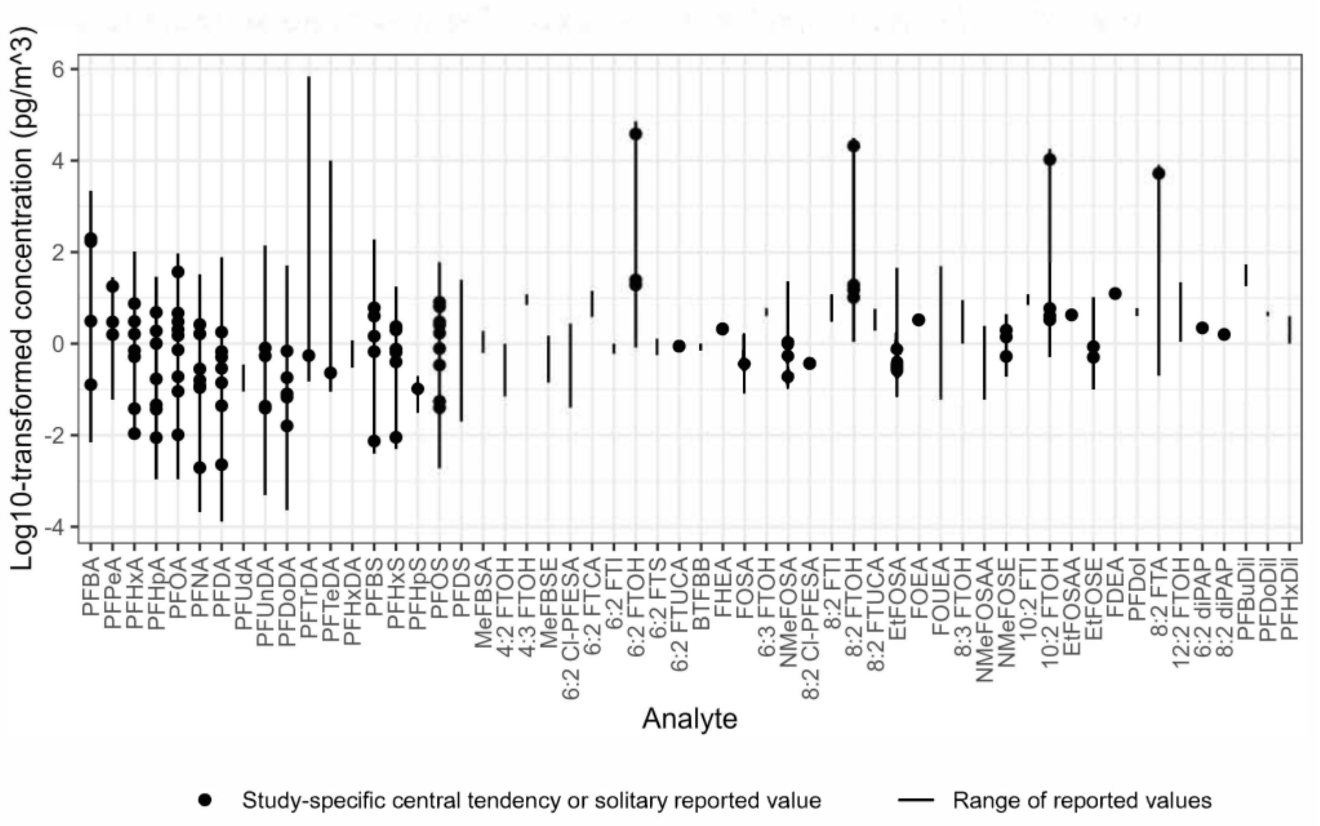
Certain PFAS are found in ambient air, with elevated concentrations observed or expected in urban areas nearest to major emission sources described in Section 2.6. These include industrial facilities that produce PFAS or use PFAS chemicals or products in manufacturing; areas where Class B firefighting foams containing fluorine are used or released; waste management facilities, including landfills and wastewater treatment plants; and areas of biosolids production and application (Borthakur et al. 2022; Barton et al. 2006; Ahrens et al. 2011; Liu et al. 2015).

As discussed in Section 5.3.2, short-range atmospheric transport and deposition may result in PFAS contamination in terrestrial and aquatic systems near points of significant emissions, contaminating soil, groundwater, and other media of concern (Davis et al. 2007), as well as several miles from industrial emission sources (Shin et al. 2011; Post, Cohn, and Cooper 2012) (NYS DOH 2016; NH DES 2017; VT DEC 2016). Releases of ionic PFAS from factories are likely tied to particulate matter (Barton et al. 2006[241]), which settle to the ground in dry weather and are also wet-scavenged by precipitation as discussed in Section 5.3.2. Models indicate that deposition depends on amount of PFAS emissions, local topography, particle size, weather patterns, and release characteristics such as smokestack height, effluent flow rate, and effluent temperature. In addition to short-range transport and deposition, long-range transport processes are responsible for a wide distribution of PFAS across the earth, as evidenced by their occurrence in biota and environmental media in remote regions as far as the Arctic and Antarctic. Long-range transport processes and effects are similar to atmospheric transport of other recalcitrant contaminants.

6.1.1 Outdoor Air

Concentrations of perfluoroalkyl acids such as PFOA and PFOS reported in outdoor air in the recent scientific literature (2017–2022) typically fall within a range of about 1–30 pg/m^3 (picograms/cubic meter) (Figure 6-1A). However, near major industrial sources, including fluorochemical manufacturing complexes in China (Zhao et al. 2020) and South Korea (Lee et al. 2020; Lin et al. 2020; Seo et al. 2019), maximum PFOA concentrations in the range of about 50–200 pg/m^3 have been reported. In the United States, concentrations of PFOA as high as 900,000 pg/m^3 have been observed near a large manufacturing facility in Parkersburg, West Virginia (Barton et al. 2006). PFOS concentrations greater than 2,000 pg/m^3 have also been observed in outdoor air near major fluorochemical manufacturing complexes in South Korea (Seo et al. 2019). Concentrations of PFBA have been observed in the hundreds of pg/m^3 at a number of global monitoring sites and at concentrations greater than 1,000–2,000 pg/m^3 at sites in Canada (Rauert et al. 2018).

The literature range of concentrations of volatile PFAS such as FTOHs is in the hundreds of pg/m^3 in outdoor air (Figure 6-1A). Atmospheric transport and deposition of PFAS occur on regional and global scales, suggesting that low-level concentrations detected in soil or other media are not necessarily indicative of a local source (Section 5.3.2). More information is included in Section 17-1, Media-Specific Occurrence Tables.



Sources: Casas et al. (2020), Casas et al. (2021), Lee et al. (2020), Lin et al. (2022), Morales-McDevitt et al. (2022), Rauert et al. (2018a), Rauert et al. (2018b), Seo et al. (2019), Sha et al. (2022), Wang Q. et al. (2022), Wang S. et al. (2022), Yamazaki et al. (2021), Zhao et al. (2017), Zao et al. (2020), Zhou et al. (2021)

Figure 6-1A. Observed PFAS concentrations in outdoor air.

Source: Figure developed using ggplot2 (Wickham 2016)

6.1.2 Indoor Air

PFAS have also been observed in indoor air and dust in homes, offices, and other indoor environments (Figure 6-1B). Indoor air concentrations of certain PFAS can be higher than outdoor air concentrations due to the presence of indoor sources (Fromme et al. 2015; Fraser et al. 2012; Goosey and Harrad 2012; Shoeib et al. 2011; Kaiser et al. 2010; Langer, Dreyer, and Ebinghaus 2010; Strynar and Lindstrom 2008; Shoeib et al. 2004). Examples of indoor sources of potential PFAS exposure include stain- and water-resistant coatings used on a number of consumer products, such as carpets, upholstery, clothing, grease-resistant paper, food packaging, and nonstick cookware and ingredients in cleaning products, personal care products, cosmetics, paints, varnishes, and sealants (ATSDR 2019; Liu et al. 2015; Liu et al. 2014) (Gewurtz et al. 2009; Guo et al. 2009). In the recent literature (2017–2022), PFOA concentrations in PM2.5 collected from indoor air across 17 kindergartens in Hong Kong ranged from about 200–1,900 pg/m^3 (Li et al. 2021). In a study of 57 households in eastern Finland, concentrations of PFOA and PFOS ranged from nondetect to about 100 pg/m^3 and 7 pg/m^3, respectively (Winkens et al. 2017).

Concentrations of volatile PFAS such as FTOHs have been reported on the order of 10,000–50,000 pg/m^3 in schools, homes, and offices. Concentrations of FTOHs have been observed in excess of 300,000 pg/m^3 inside commercial buildings (Fromme et al. 2010) and as high as 255,000 pg/m^3 in residences in the area of Oslo, Norway (Padilla-Sanchez et al. 2017). More information is included in Section 17-1, Media-Specific Occurrence Tables.

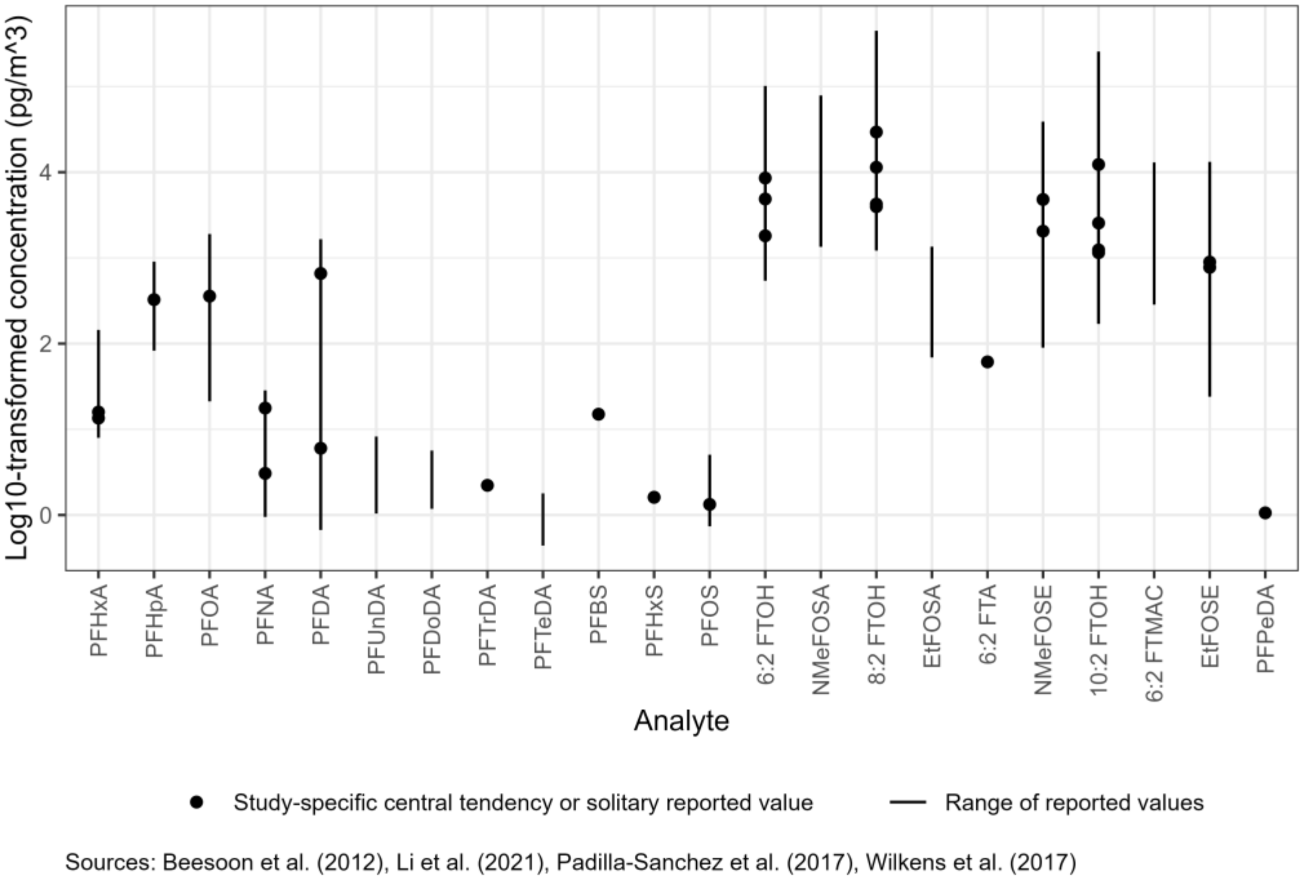
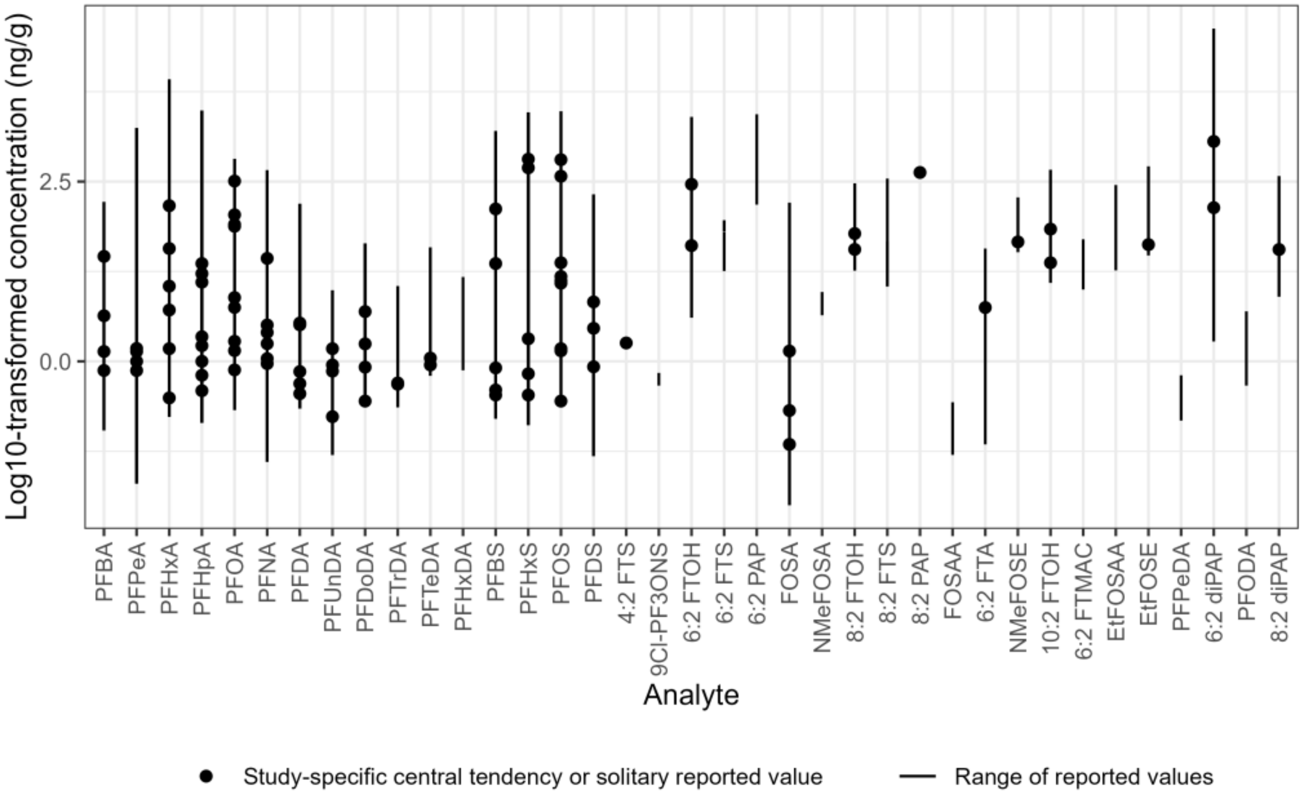


Figure 6-1B. Observed PFAS concentrations in indoor air.

Source: Figure developed using ggplot2 (Wickham 2016)

6.1.3 Settled Dust

PFAS have been measured in settled dust from floors and other surfaces and from samples collected from air conditioner filters, vacuum cleaner bags, and carpets from a variety of indoor environments, including schools and universities, preschools and childcare facilities, homes, and workplaces (Young et al. 2020; Zheng et al. 2019; Ao et al. 2019; Besis et al. 2019; de la Torre et al. 2019; Giovanoulis et al. 2019; Byrne et al. 2017; Beesoon et al. 2012). The literature range of concentrations of PFAS in dust in indoor environments vary over many orders of magnitude (Figure 6-1C). Concentrations of PFOA and PFOS range from nondetect to about 650 ng/g and 3,000 ng/g, respectively. Fluorotelomers have also been observed in indoor dust, ranging from nondetect to about 2,500 ng/g for FTOHs. Fluorotelomer phosphate diesters (diPAPs) were reported in a study of preschools in the area of Stockholm, Sweden, and ranged from nondetect to greater than 42,000 ng/g (Giovanoulis et al. 2019). More information is included in Section 17-1, Media-Specific Occurrence Tables.



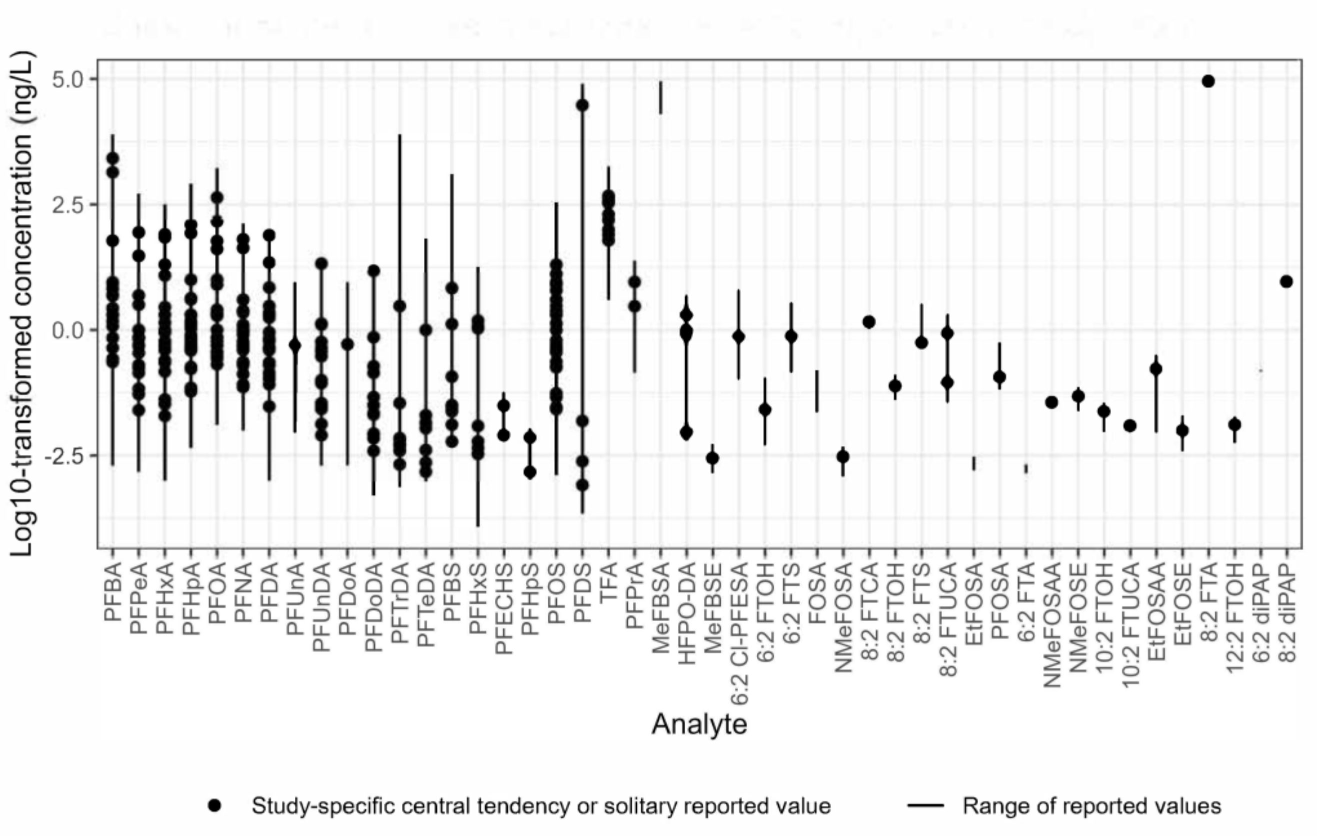
Sources: Ao et al. (2019), Beesoon et al. (2012), Besis et al. (2019), Byrne et al. (2017), de la Torre et al. (2019), Giovanoulis et al. (2019), Young et al. (2020), Zheng et al. (2020)

Figure 6-1C. Observed PFAS concentrations in settled dust.

Source: Figure developed using ggplot2 (Wickham 2016)

6.1.4 Precipitation

PFAS have also been observed in precipitation and other samples impacted by precipitation, including rainwater, surface and subsurface snow, sea ice, and meltwater. The literature range of concentrations of PFAS in precipitation vary over many orders of magnitude (Figure 6-1D) (Casas et al. 2021; Pike et al. 2020; Xie et al. 2020; Chen et al. 2019; MacInnis et al. 2019; Wang et al. 2019; Lu et al. 2018; Casal et al. 2017; Yeung et al. 2017; Zhen et al. 2015; Taniyasu et al. 2008; Barton, Kaiser, and Russell 2007; Kim and Kannan 2007). Lower levels of PFAS have been observed in precipitation from remote locations such as the Arctic and Antarctic as compared to more populated and urbanized, continental regions. Concentrations of perfluoroalkyl acids in precipitation, such as PFOA and PFOS, were typically <1 ng/L in remote regions, while concentrations greater than 1,600 ng/L and 50 ng/L were observed, respectively, in continental regions. Fluorotelomers, including FTOHs, fluorotelomer sulfonic acid (FTSA), and fluorotelomer unsaturated carboxylic acids (FTUCAs), have been observed in precipitation with concentrations of FTOHs and FTSA exceeding 100 ng/L (Chen et al. 2019; Zhen et al. 2015) and FTUCAs ranging from nondetect to about 2 ng/L (Chen et al. 2019; Taniyasu et al. 2008). Heptafluoropropoxy propanoic acid (HFPO-DA), or GenX, has also been found in precipitation as high as 5 ng/L (Pike et al. 2020). More information is included in Section 17-1, Media-Specific Occurrence Tables.



Sources: Barton et al. (2017), Casal et al. (2017), Casas et al. (2021), Chen et al. (2019), Garnett et al. (2021), Gewurtz et al. (2019), Kim and Kannan (2007), Lu et al. (2018), MacInnis et al. (2019), Pike et al. (2020), Taniyasu et al. (2008), Wang et al. (2019), Xie et al. (2020), Yeung et al. (2017), Zhen et al. (2015)

Figure 6-1D. Observed PFAS concentrations in precipitation.

Source: Figure developed using ggplot2 (Wickham 2016)

6.2 Soil, Sediment, and Biosolids

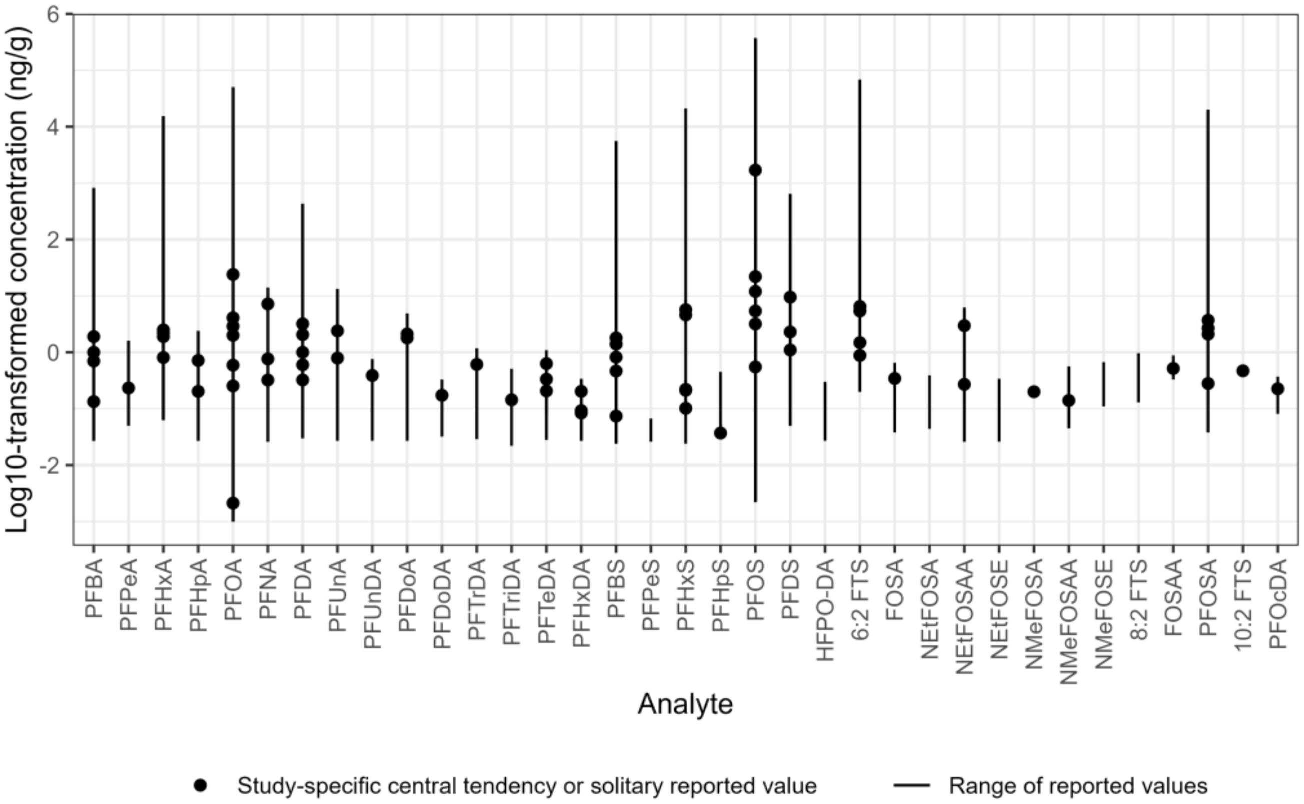
PFAS occurrence in soil and sediment can result from direct inputs (for example, AFFF releases or industrial discharge) or indirectly through exposure to impacted media (for example, atmospheric deposition, landfill leachate, or wastewater effluent). Another focus of current research is agricultural application of biosolids, compost, or pesticides, all of which are potential PFAS sources (Table 2-6). As a result of these inputs, soil and sediment may act as secondary sources of PFAS via leaching to groundwater and runoff to surface water through leaching and percolation processes, respectively. The concentration and distribution of PFAS observed in soils, sediments, and biosolids is complex and can be a function of source (direct versus indirect), site-specific considerations (for example, TOC, particle surface charges, and phase interfaces, see Section 5.2.3) and PFAS-specific chemistry (for example, alkyl chain length and ionic functional group). PFOS, PFOA, and other long-chain PFAAs are typically the predominant PFAS reported in surface soils and sediments (Cai et al. 2022; Rankin et al. 2016; Strynar et al. 2012; Zhu et al. 2019). Based on the increasing interest in biosolids, data related to that topic have been compiled separately from other sources.

6.2.1 Soil

Surface and subsurface soil are a significant reservoir for PFAS released to the environment. Numerous studies show individual PFAS concentrations in soil vary across multiple orders of magnitude, found at low concentrations (<1 ug/kg) globally even in remote areas, and at concentrations exceeding 1,000 µg/kg at industrial and AFFF release sites (Rankin et al. 2016; Brusseau et al. 2020) (Figure 6-2A).

Improving the understanding of anthropogenic background PFAS concentrations for comparison to site data has been a focus of recent work. A survey of anthropogenic background concentrations of PFAS in soil found PFOS ranging from 0.003 to 162 ug/kg and PFOA from 0.01 to 124 ug/kg (Brusseau et al. 2020). Although not focused on contaminated sites, many of the surveys were in or near populated regions and included agricultural fields. Recent studies in Maine and New Hampshire also focused on anthropogenic background soil levels without identified sources and in those studies PFOS ranged from nondetect to 5.4 and PFOA from nondetect to 5.3 ug/kg for the combined data. Median data for detected PFOS were 0.37 and 0.94 ug/kg, and for PFOA, 0.17 and 0.76 ug/kg for Maine and New Hampshire, respectively (MEDEP 2022; Santangelo et al. 2022). In contrast, data at known PFAS release sites such as fire training areas and biosolids application sites showed maximum concentrations of PFAS that may exceed anthropogenic background by several order of magnitude. PFOS and PFOA in fire training areas and other source zones may be as high as 373,000 and 50,000 ug/kg respectively, though the median values for AFFF source zones were much lower—18 and 1.4 ug/kg for PFOS and PFOA (Brusseau et al. 2020).

Published data on soil PFAS concentrations in industrial settings are limited, and can be highly variable, depending on the nature of PFAS release and proximity to the source. More information is included in Section 17-1, Media-Specific Occurrence Tables. Additional detail on AFFF is found in Section 3.



Sources: Brusseau et al. (2020), Groffen et al. (2019), Sanborn Head & Associates (2022), Sorengard et al. (2022), USGS (2022), Wang et al. (2018)

Figure 6-2A. Observed PFAS concentrations in site and anthropogenic background soil.

Source: Figure developed using ggplot2 (Wickham 2016)

6.2.2 Sediment

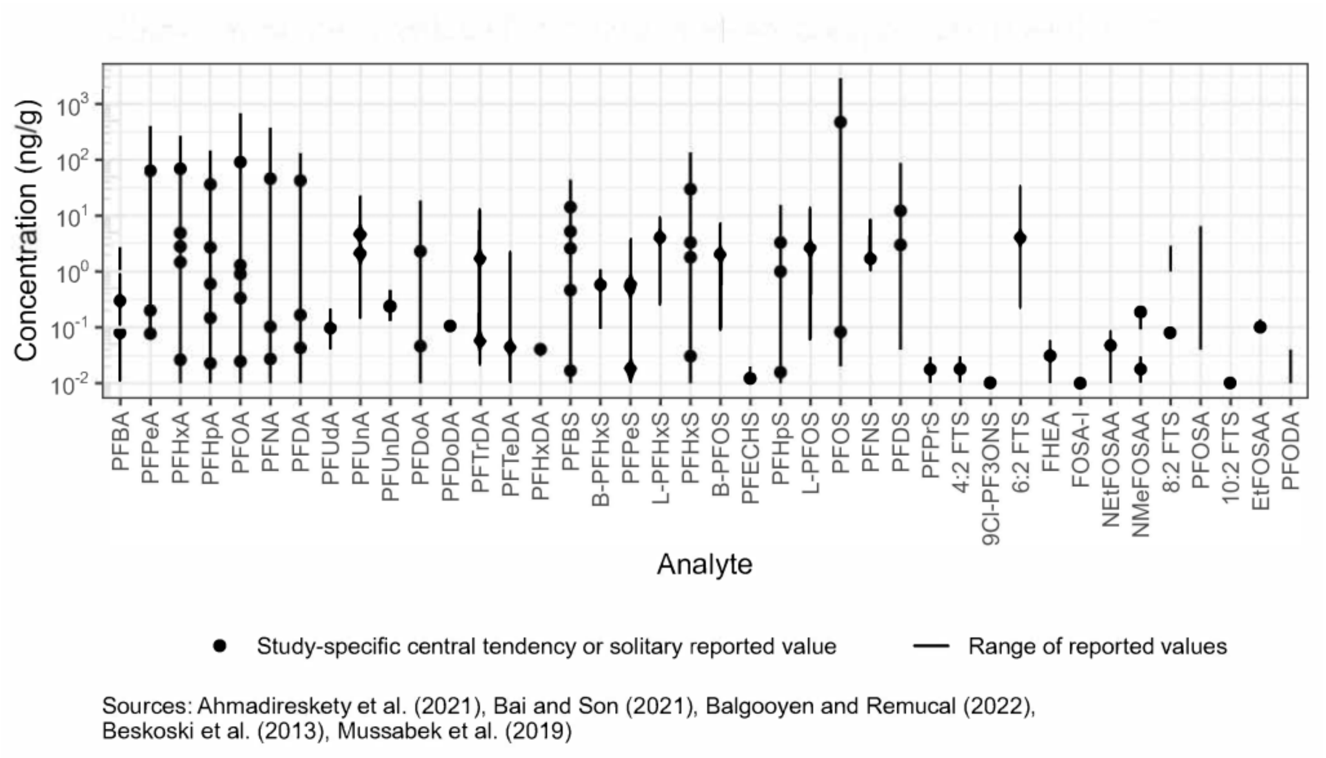
Direct discharge of AFFF, leachate, wastewater effluent, and runoff to surface waters and subsurface discharge of contaminated groundwater to surface water has resulted in PFAS impacts to freshwater and marine sediments. Detected concentrations for surface sediments in lakes and rivers reported in the literature generally range from below detection limit to approximately 100 µg/kg, and concentrations and relative distributions of PFAS are variable depending upon types of sources and distance from point sources (Figure 6-2B).

A study of 48 lakes and two reservoirs with different limnological and geographic settings across China found surface sediment concentrations for a sum of detected PFCAs + PFOS ranged from 0.086 to 5.79 ng/g with a detection frequency of 100%. These samples collected in 2010–2013 showed that PFAS concentrations correlate to parameters such as TOC, nitrogen, and phosphorus in sediment (Qi et al. 2016).

A study from the Great Lakes (Codling et al. 2018) evaluated the use of dated sediment cores to assess PFAS deposition trends and analyzed for 22 PFAS. Reported values for the sum of PFAS in cores ranged from nondetect to 68.3 ug/kg dry weight, with the max value attributed to a detection of PFHpA of 46.6 µg/kg at that location. Concentrations typically increased with time in the cores. Grab samples were also collected, and PFOS ranged from 0.1 to 2.5 ug/kg, PFOA from nondetect to 3.0 ug/kg, and PFHpA from nondetect to 8.5 ug/kg. Concentrations in grab samples for the sum of PFAS ranged from nondetect to 26.0 ug/kg. Sediment core analysis may be effective for estimating deposition rates and fluxes for a subset of PFAS that exhibit strong sorption to sediment, with concentration at a given depth interval representing deposition during that time period (Codling et al. 2018).

A Swedish study of sediment cores in a lake and pond impacted by AFFF showed that PFOS and PFHxS were the dominant PFAS in sediment. Concentrations of PFOS and PFHxS ranged as high as 64 and 13 ng/g, respectively, and the study identified peak deposition rates occurring between 2003 and 2009, which correlated with reported activity near the water bodies (Mussabek et al. 2019).

Large precipitation or storm events can also contribute to episodic or enhanced transport of sediment and resuspension or redistribution of contamination in some environmental settings. Resampling of marine sediment locations in Florida following the passage of a hurricane found sediment concentrations of total PFAS decreased 47% averaged across nine sites. Highest concentrations of PFAS were spatially correlated to potential sources such as military installations and manufacturing facilities, and across all locations short-chain PFCAs dominated the total PFAS at 68% of locations, while long-chain PFAAs dominated the other 32% of sites (Ahmadireskety et al. 2021). Sediment in two urban watersheds showed concentrations of individual PFSAs as high as 88 ng/g, and found seasonal variability in sediment concentrations, potentially related to higher/lower water flows, or variation in organic matter and uptake during algal blooms (Bai and Son 2021). Once deposited, sediments can directly impact biota and can influence surface water concentrations. Tributary sediments with a mix of potential sources were shown to be potential secondary sources of PFAAs once those sediments were transported to a receiving water body (Balgooyen and Remucal 2022). Figure 6-2B illustrates the concentration distribution in sediment across multiple environmental settings from these recent studies. More information is included in Section 17-1, Media-Specific Occurrence Tables.



Sources: Ahmadireskety et al. (2021), Bai and Son (2021), Balgooyen and Remucal (2022), Beskoski et al. (2013), Mussabek et al. (2019)

Figure 6-2B. Observed PFAS concentrations in sediment.

Source: Figure developed using ggplot2 (Wickham 2016)

6.2.3 Biosolids

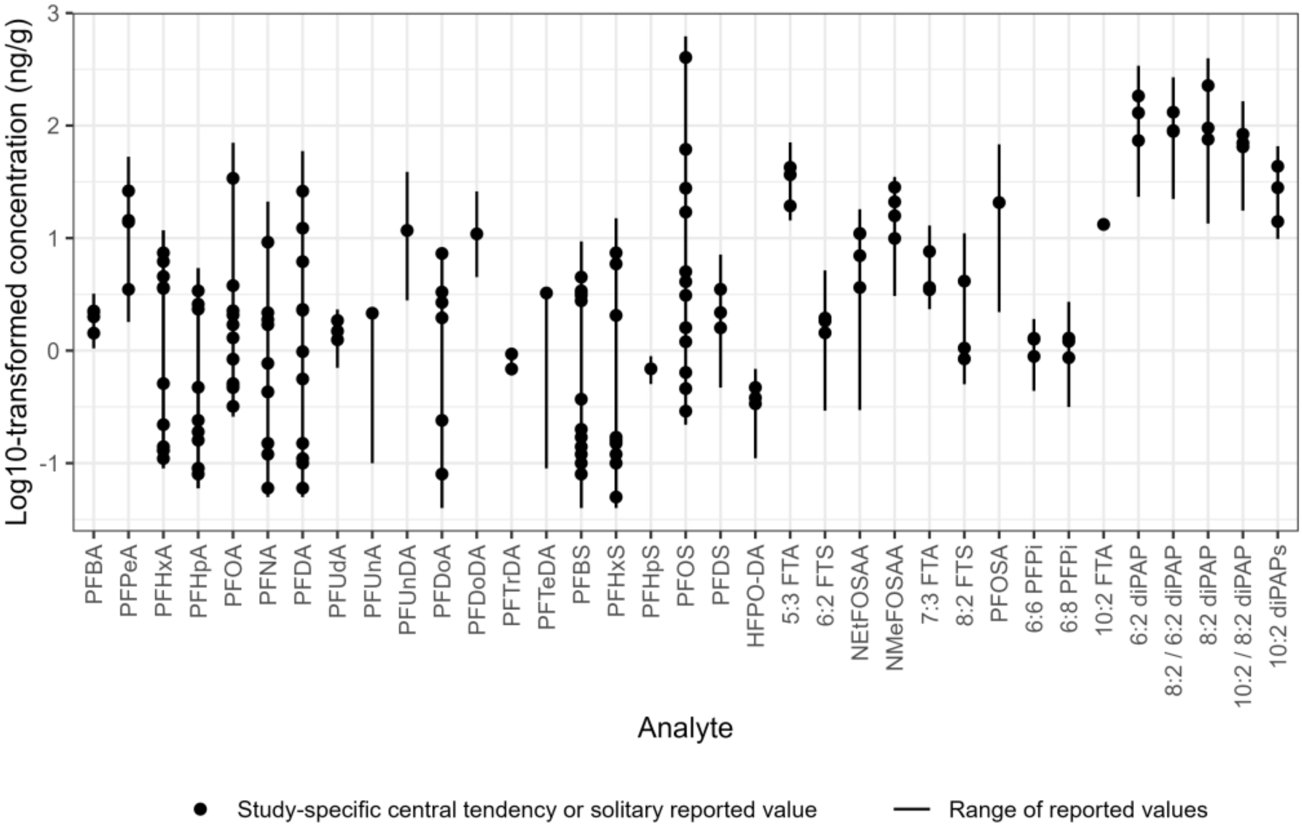
PFAS occurrence in biosolids is reported to be prevalent across the United States at a wide range of concentrations, and may be from municipal, residential, or industrial sources, or a combination of any of those sources. Biosolid designations may include “land applied,” Class A, Class B, Class C, unclassified, and mixed land-applied organic waste products. A 2013 study of archived samples of biosolids from 2001 in the United States, which targeted 12 PFAAs and PFOSA, reported mean concentrations of PFOS (403 ng/g) and PFOA (34 ng/g) with the mean values of other PFAAs ranging from 2 to 21 ng/g. With the exception of PFBA, PFBS, and PFHpA, the target PFAAs and PFOSA were detected in all samples (Venkatesan and Halden 2013). A 2021 review of reported values for biosolids, compost, and related biowastes highlighted the wide concentration range of reported PFAS (primarily PFAAs) and the relationship of biowaste source to resulting concentrations (Bolan et al. 2021). Figure 6-2C illustrates concentration ranges in biosolids for a selection of PFAS from a subset of recent data. Early studies reported that the most abundant PFAAs (see Section 2.2.3.1) found in biosolids (PFOS and PFOA) are similar to those found in wastewater effluent, although biosolids may also contain other PFAS, including long-chain PFAS (Hamid and Li 2016; Washington et al. 2010). Although multiple studies have reported data showing transformation of polyfluorinated substances to PFAAs in land-applied biosolids (Yoo et al. 2010; Sepulvado et al. 2011; Washington et al. 2010), other evidence indicates that some polyfluorinated substances remain in biosolids-amended soils for many years to decades (Yoo et al. 2010; Rich et al. 2015; Washington et al. 2018).

PFOS is the most frequently reported PFAS and typically at the highest concentration of the PFAAs most frequently reported (Clarke and Smith 2011; Gallen et al. 2018; Moodie et al. 2021; Munoz et al. 2021; Pepper et al. 2021). Target and nontarget precursor compounds are also commonly detected in biosolids, including 6:2 diPAP and 6:2 FTS (Kim Lazcano et al. 2020; Schaefer et al. 2022; Moodie et al. 2021), EtFOSAA, and cationic and zwitterionic electrochemical fluorination precursors to PFOS (Munoz et al. 2021). Biosolids tend to be enriched in long-chain PFAAs containing more than six carbon atoms (Kim Lazcano et al. 2019).

Repeated application of biosolids to agricultural soil can result in PFAS accumulation in shallow soil depths, and eventual leaching to groundwater, as well as uptake by agriculturally sourced products (Ghisi et al. 2019). “Shallow soil” in this context will be variable depending on the crop or farm practices. For example, Maine considers 0–2 feet to be the “plow layer” (ME DEP 2021), whereas USEPA refers to shallow soil “extending to site-specific depths that can be sampled easily by manual methods,” generally 0–12 inches (USEPA 2020). Based on the biosolid application rates in the United States and the mean total PFAS concentrations observed for archived biosolids from 2001, it is estimated that 1,375–2,070 kg of PFAS may have been added to agricultural land annually across the United States during that time (Venkatesan and Halden 2013). Data for more recent testing of biosolids and compost typically show lower concentrations of PFAAs and lower annual application rates (Bolan et al. 2021).

PFAS concentrations in soils at sites with applied biosolids or sludge will vary depending upon application rates, frequency, duration, geochemical and hydrogeologic factors, and concentration of PFAS in the applied material. Perfluorocarboxylic acids (PFCAs) and perfluoroalkylsulfonic acids (PFSAs) have been observed in surface soils treated with biosolids at 1 and 2 orders of magnitude higher than global anthropogenic background soils, respectively (Johnson 2022). In contrast, another study observed that even after decades of land application, the concentration and accumulation of PFAS in soils where biosolids were applied was comparatively low. In addition, the study observed that there was ~73% attenuation of measured PFAS from the shallow soil sample at 30.5 cm to the deepest interval of 183 cm (Pepper et al. 2021). This variability of reported data illustrates the importance of site-specific history and conditions to resulting concentrations in soil at land application sites.

Ultra-short-chain PFAS, certain precursors to PFAS, and new generation PFAS potentially account for a significant fraction of the total fluorine present in biosolids, but are largely unquantifiable by current standard methods (Kim Lazcano et al. 2020; Munoz et al. 2021; Schaefer et al. 2022). The highest average minimum and maximum concentrations observed in recent publications were n:2 polyfluoroalkyl phosphoric acid esters, polyfluoroalkyl phosphates, and fluorotelomer phosphates (diPAPs). In addition to diPAPs, perfluoroalkane sulfonamido acetic acids (FASAAs), perfluorooctane sulfonamides, and fluorotelomer sulfonic acids (FTS) were abundant (Munoz et al. 2021; Schaefer et al. 2022). This suggests that limiting PFAS analysis of biosolids to the standard suite of analytes may not account for a substantial fraction of the overall fluorine mass (Schaefer et al. 2023; Thompson et al. 2023). Of the perfluoroalkyl acids (PFAAs), long-chain perfluoroalkyl sulfonic acids (PFSAs) were present at the highest concentrations, likely due to their hydrophobicity and greater tendency to remain sorbed to soils within the vadose zone (Figure 6-2C). More information is included in Section 17-1, Media-Specific Occurrence Tables.



Sources: Pepper et al. (2021), Schaefer et al. (2022), Venkatsesan and Halden (2013), Venkatsesan and Halden (2014)

Figure 6-2C. Observed PFAS concentrations in biosolids and land-applied soil.

Source: Figure developed using ggplot2 (Wickham 2016)

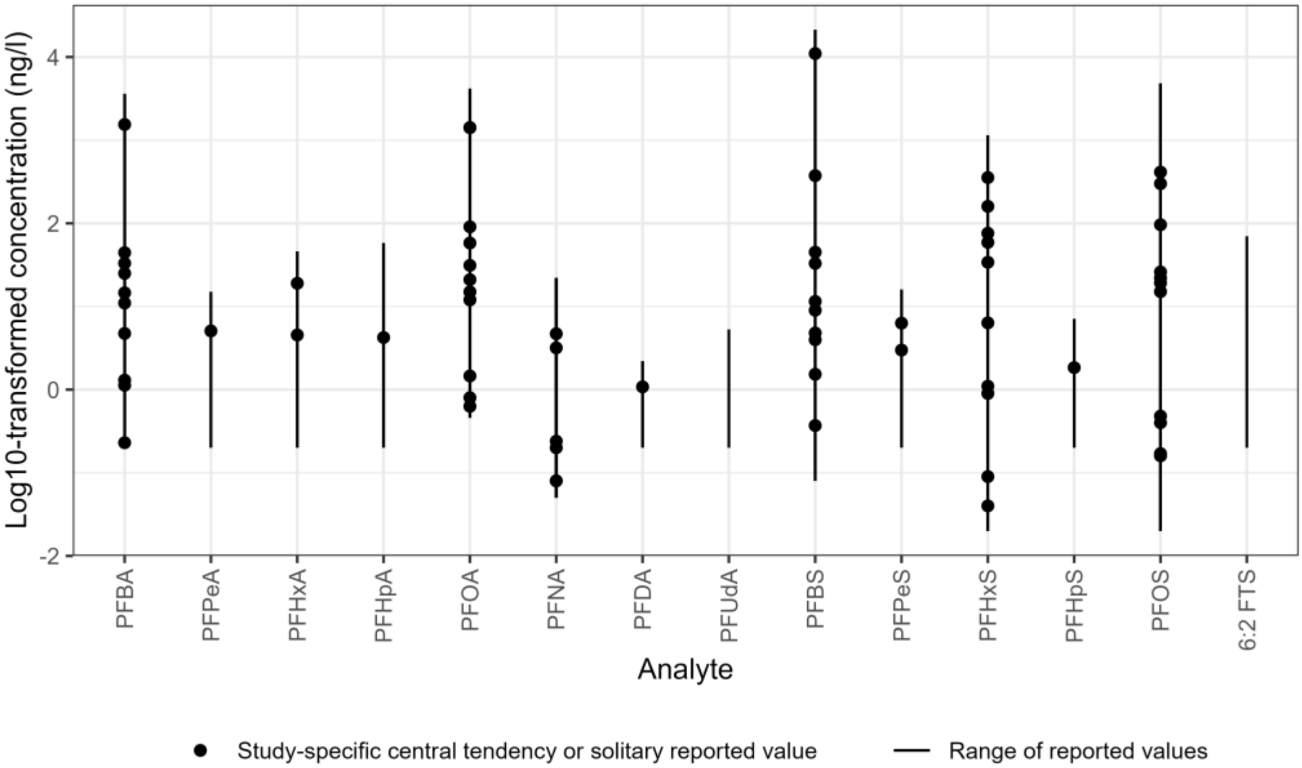
6.3 Groundwater

USEPA has assembled an extensive data set of the occurrence of six PFAAs in public drinking water. This data set is the result of required monitoring of approximately 4,900 public water systems (all large systems serving more than 10,000 people, plus a subset of smaller systems) for six PFAAs in finished drinking water at points of entry to the drinking water distribution system. The study was conducted between 2013 and 2015 under the third Unregulated Contaminant Monitoring Rule (UCMR3) and included the results from treated water that originated from groundwater wells (n = 22,494), groundwater under the direct influence of surface water (n = 436), surface water sources (n = 13,228), and mixed sources (n = 814) (USEPA 2017). A summary of the UCMR3 occurrence data, including analytical reports, is included in Section 8.2.2.4. An analysis conducted on the nonfinalized UCMR3 data set found that one or more PFAAs were detected in 4% of the reporting public water systems (USEPA 2017); however, groundwater sources had approximately double the detection rate of surface water sources (Hu et al. 2016).

As of June 2022, USEPA issued interim health advisories for PFOA and PFOS in drinking water (USEPA 2022). These replace the former values USEPA issued in 2016 of 70 ng/L (USEPA 2016, 2016). The interim values of 0.004 ng/L for PFOA and 0.02 ng/L for PFOS are lower than the minimum detection limit of 0.52 ng/L for drinking water methods (ITRC Table 11-3, PFAS Analytical Methods Excel file). Therefore, all detected concentrations would be above the interim health advisories. Detections were geographically widespread but showed quantifiable associations with suspected sources, including industrial sites, military fire training areas, AFFF-certified airports, and wastewater treatment facilities (Hu et al. 2016). Individual states are collecting information on PFAS occurrence in smaller public water supplies such as schools and mobile home parks that do not meet the threshold to comply with the Unregulated Contaminant Monitoring Rule, so were not sampled during UCMR3, and for which data are often publicly available, for example, in New Hampshire at NH DES (2020). UCMR5 will include a larger list of PFAS analytes, public water systems (PWSs) serving 3,300 or more persons, and up to 800 smaller PWSs (USEPA 2021).

Groundwater occurrence data collected as part of domestic and international studies have also characterized the range of

PFAS concentrations associated with AFFF release sites, industrial facilities, and landfills; examples of these study results are provided in Figure 6-3. More information is archived as a Section 17.1 PDF, found under Archived External Tables and Sections on the home page of this site.



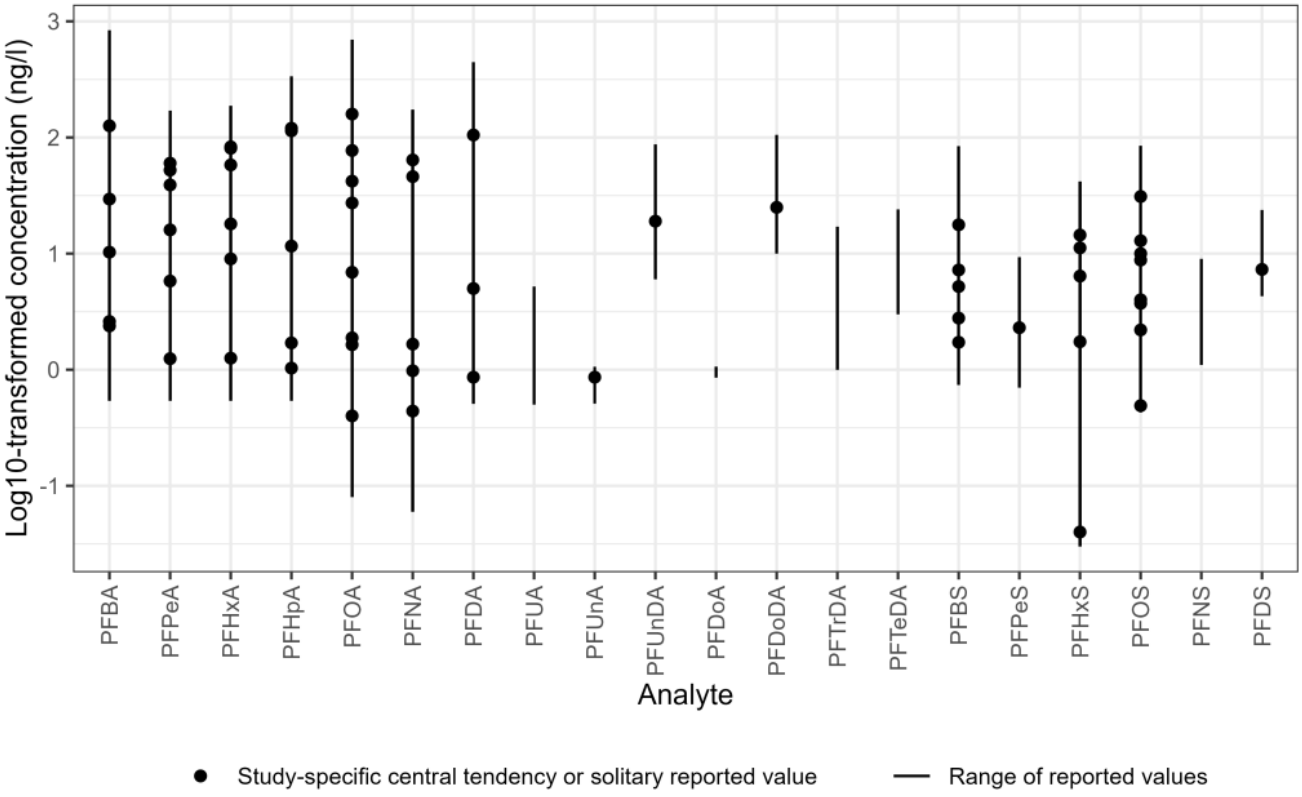
Sources: Cao et al. (2019), Chen et al. (2016), Hepbern et al. (2019), Bao et al. (2019a), Liu et al. (2019), McMahon et al. (2022), MDE (2021), Sammut et al. (2019), Schaefer et al. (2018), Sharma et al. (2016), Wang et al. (2016a)

Figure 6-3. Observed PFAS concentrations in groundwater.

Source: Figure developed using ggplot2 (Wickham 2016)

6.4 Surface Water

Freshwater, marine water, and stormwater PFAS concentrations usually depend on proximity to the point of release and source concentrations. In addition to releases associated with identified sources, stormwater runoff from nonpoint sources may contribute significant loads of PFAS to surface water (Wilkinson et al. 2017; Zushi and Masunaga 2009). The sorption of PFAS to suspended solids may affect surface water PFAS concentrations. Suspended microplastics may also influence PFAS in surface water (Llorca et al. 2018). Figure 6-4 presents examples of observed PFOS and PFOA surface water concentrations, organized by source type. In addition to PFOS and PFOA, many other PFAS have been observed in surface waters, including compounds other than PFAAs. For example, a recent study found perfluoro-2-propoxypropanoic acid (PFPrOPrA also known as the GenX chemical HFPO-DA) in untreated water drawn from the Cape Fear River in North Carolina at concentrations up to 560 ng/L, and GenX was just one of many non-alkyl acid PFAS identified (Sun et al. 2016). Surface water occurrence is also an important source of drinking water supply impacts (USEPA 2018; Post et al. 2013). More information is archived as a Section 17.1 PDF, found under Archived External Tables and Sections on the home page of this site.



Sources: Bai et al. (2020), Cao et al. (2019), Chen et al. (2016), Garnett et al. (2021), Gewurtz et al. (2019), Sharma et al. (2016)

Figure 6-4. Observed PFAS concentrations in surface water.

Source: Figure developed using ggplot2 (Wickham 2016)

6.5 Biota

Because PFAS are distributed globally and have a propensity to bioconcentrate, they have been found in fish, wildlife, and humans. PFAAs, particularly PFOS, are typically the dominant PFAS detected in biota (Houde et al. 2011). PFAA concentrations in biota are influenced by uptake and elimination of both PFAAs and their precursors, as well as biotransformation rates of PFAA precursors (Asher et al. 2012; Gebbink, Bignert, and Berger 2016). Therefore, concentrations of PFAAs observed in biota at one location may not reflect concentrations in other environmental media.

6.5.1 Plants

Studies show evidence of uptake and accumulation of PFAAs by plants in several settings and applications, including both controlled experiments and field investigations. Concerns about introducing PFAAs into livestock or crops have led to investigations of uptake and accumulation in plants (Section 5.6). Uptake mechanisms and the extent to which native plant species remove and accumulate PFAS have not been as well studied.PFAS may be introduced to plants from soil, water, or air by:

- irrigation water
- the application of biosolids or sludge-amended soils
- the application of pesticides
- soil and groundwater at PFAS sites or near releases of PFAS
- exposure through contact with rainwater and atmospheric deposition

Studies demonstrating plant uptake of PFAAs have focused on irrigated crops (Stahl et al. 2009; Scher et al. 2018; Bolan et al. 2021), crops in biosolids-amended soil (Yoo et al. 2011; Blaine et al. 2013; Blaine et al. 2014; Felizeter et al. 2021; Costello and Lee 2020; Knight et al. 2021), and aquatic plants in constructed wetlands (Chen, Lo, and Lee 2012). PFAS have also been found in pesticides (Zabaleta et al. 2018; Lasee et al. 2022). USEPA's Analytical Chemistry Branch repeated the analyses conducted by Lasee et al. (2022 for PFAS and conducted additional analyses. In USEPA's results no PFAS were detected above the method detection limits (USEPA 2023).Other investigations have focused on flora exposed to PFAAs in the natural environment (Zhang et al. 2015) or near known PFAS sources (Shan et al. 2014). Based on bioconcentration factors discussed in Section 5.6, concentrations in plants will generally reflect the same concentrations in soil and, for trees with deep roots, groundwater (Gobelius, Lewis, and Ahrens 2017).

6.5.2 Invertebrates

Invertebrates act as the main component of the food web base and play a key role in the dynamics of biomagnification. Aquatic invertebrates can reside in the water column, as well as on (or in) the sediment substrate. In higher trophic level organisms, PFOS has been documented as the dominant PFAS, with concentrations increasing up the food chain, while PFOA has a lower bioaccumulation potential with similar concentrations among species of different trophic level animals (Houde et al. 2011; Conder et al. 2008). In invertebrates, both PFOS and PFOA have maximum values within similar ranges (Ahrens and Bundshuh 2014). A recent review of PFAS occurrence in marine and estuary invertebrates (i.e., mollusks and crustaceans) found that patterns of PFAS bioaccumulation can vary slightly between these taxa, but historical differences in sampling and analytical methods complicate comparisons to more recent investigations (Giffard et al. 2022[2675]). Studies present a PFAS range of approximately 0.1–10 mg/kg in invertebrate tissue, although their sources predominantly address marine organisms (Houde et al. 2011). Similar levels of PFOS have been found in freshwater invertebrates (< 2–4.3 mg/kg) with a BCF (biota/water) estimated at 1,000 L/kg (Kannan et al. 2005). Concentrations of PFOS, PFCAs, and heptadecafluorooctane sulfonamide (PFOSA) have been observed in Lake Ontario invertebrates, ranging from < 0.5 to 280 mg/kg (Martin et al. 2004). The PFAS concentrations in invertebrates were greater than in fish from this lake.

In soil invertebrates, current research indicates that bioaccumulation potential of PFOS is low, as is biomagnification (increasing concentrations in predators over their prey) from lower to higher trophic level organisms (CEPA 2017). In biosolids-amended soils, the mean PFAS BAFs in earthworms have been found to range from 2.2 (PFOA) to 198 (PFDoA) g dry weight (dw) soil/g dw worm (Navarro et al. 2016). Maximum BAFs in earthworms for all PFAS types have been observed at <45 g dw soil/g dw worm for biosolids-amended soils and <140 g dw soil/g dw worm for soils contaminated with AFFF (Rich et al. 2015).

6.5.3 Fish

Accumulation of PFAS in fish is well documented, particularly for PFOS, longer chained PFCAs (with eight or more carbons), and perfluorodecane sulfonate (PFDS) (Houde et al. 2011; Martin et al. 2013; Conder et al. 2008). PFOS generally has the highest concentrations in fish due to the historically high use of this chemical and its bioaccumulation potential (Houde et al. 2011). PFDS, long-chain PFCAs, and other PFAS have also been measured in fish (Houde et al. 2011; Fakouri Baygi et al. 2016).

In fish, PFOS tends to partition to tissues of high protein density, including the liver, blood serum, and kidney (Falk et al. 2015; Ng and Hungerbühler 2013). This distribution pattern is contrary to other persistent chemicals, which tend to partition to adipose tissue. Concentrations of PFOS and other PFAAs tend to be higher in whole fish samples compared with fillets given that a major fraction of PFAAs is found in the carcasses of fish rather than fillets (Fliedner et al. 2018). PFAA concentrations sometimes increase with fish size; however, the relationship with fish size is not consistent as observed for other contaminants such as mercury (Babut et al. 2017; Gewurtz et al. 2014).

Fish data for PFOS collected near known sources (for example, AFFF sites) from some key studies are summarized in Figure 6-5. More information is archived as a Section 17.1 PDF, found under Archived External Tables and Sections on the home page of this site.

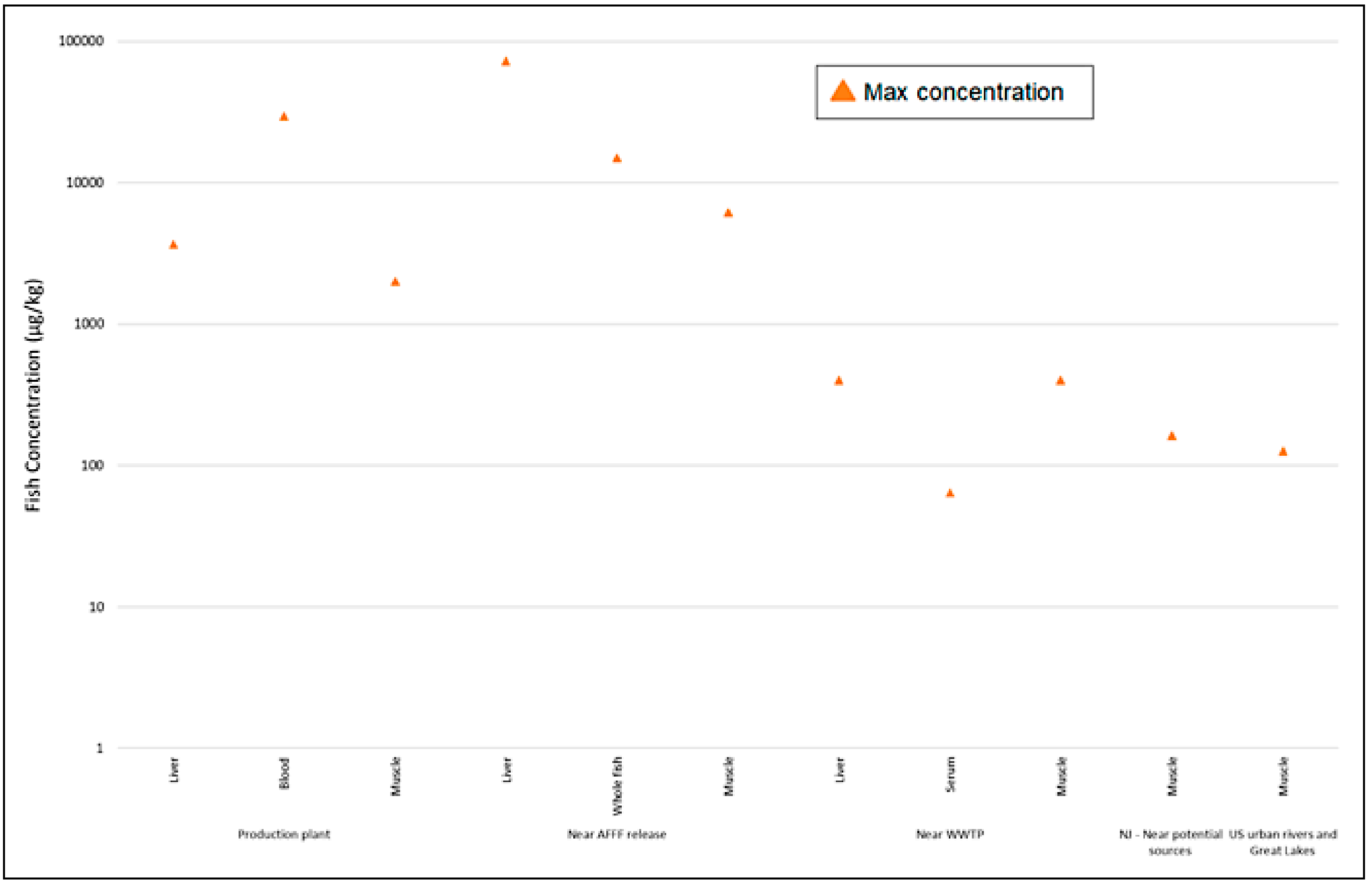


Figure 6-5. Observed PFAS concentrations in fish.

6.5.4 Vertebrates

Most research addressing PFAS concentrations in vertebrates focuses on temporal trends in animals at the top of the food chain, such as piscivorous birds (for example, osprey) and mammals (for example, dolphins, seals). The concentrations are often reported in protein-rich organs known to concentrate PFAS. For example, to evaluate temporal trends between 2002 and 2014, levels of PFAS were measured in liver samples of Indo-Pacific humpback dolphins and finless porpoises (136–15,300 and 30.5–2,720 ng/g dw, respectively) (Gui et al. 2019). Livers of Beluga whales in the Artic were the only organ sampled to better understand the relative bioaccumulation of persistent organic compounds (Reiner et al. 2011). These data using top marine predators as “sentinels” of PFAS are important in terms of assessing whether concentration trends are increasing or decreasing in the global environment.

PFAS bioaccumulation in terrestrial human food sources (livestock, livestock products, and game) is a critical area of occurrence discussions, and few research or review articles currently exist. Animals raised for food and wildlife species may come into contact with PFAS through contaminated air, water, soil, substrate, or feed. However, the extent to which these exposures contribute to PFAS concentrations in food products is not extensively researched (Death et al. 2021). A study focused on livestock drinking water and grazing found that sites with mean livestock drinking water concentrations as low as 0.003 µg PFOS/L may exceed action levels or advisory levels for PFOS in cattle meat (Mikkonen et al. 2023). Current understanding is that most PFAS accumulates in muscle tissue and milk (Brake et al. 2023). Some state agencies are conducting sampling surveys of game animals and issuing “Do Not Eat” advisories (ME DIFW 2023; MPART 2023).

Updated September 2023.

7 Human and Ecological Health Effects of select PFAS

The PFAS Team developed a Human and Ecological Effects training video with content related to this section.

This section discusses both the information related to assessing health effects of PFAS in humans (Section 7.1) and the adverse effects on ecological (nonhuman) species (Section 7.2). This is an active area of scientific research. Section 7.1 provides information on human biomonitoring and exposure, toxicokinetics, toxicology in mammalian species, and human epidemiology for long-chain and short-chain PFAAs and the per- and polyfluorinated ether carboxylates (PFECAs) commonly known as the GenX chemicals and ADONA. The section is supplemented by additional material on each of these topics, which is included as Section 17.2. Section 7.2 is organized to include ecological toxicology information on invertebrates (aquatic, benthic, terrestrial), vertebrates (fish, birds, reptiles, amphibians, mammals), and plants.

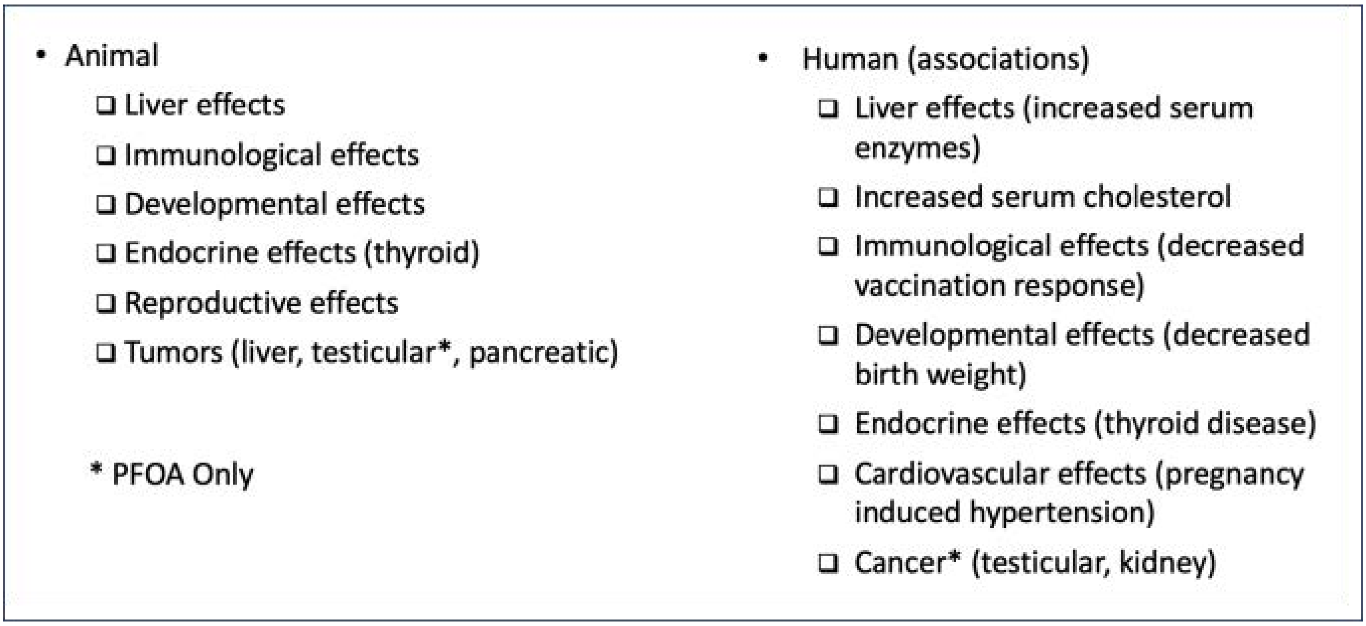
For further information on the scientific names and carbon chain length of PFAAs addressed in these sections, see Section 2.2 of this document. Use of the human health effects information in guidance values is discussed in Section 8.3 and in site risk assessment in Section 9.1.

Section Number	**Topic**
7.1	Human Health Effects
7.2	Ecological Toxicology

7.1 Human Health Effects

The PFAS discussed in this section and in Section 17.2 include perfluorocarboxylic acids (PFCAs) with 4–14 carbons and perfluorosulfonic acids (PFSAs) with four or more carbons. Also covered are several PFECAs that are used as replacements for PFOA as processing aids in production of certain fluoropolymers, including the GenX chemicals, hexafluoropropylene oxide dimer acid (HFPO-DA) and its ammonium salt, (also known as perfluoro-2-propoxypropanoic acid [PFPrOPrA] and ammonium 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propanoate, respectively) and 4,8-dioxa-3H-perfluorononanoate, commonly known as ADONA. In addition, Section 17.2.6 reviews other ether and polyether PFAS, fluorotelomer alcohols, and fluorotelomer sulfonic acids. They are included because they are of current interest and health effects data are available. There is little or no publicly available health effects information for most of the many other PFAS used in commerce (Section 2.5), including precursors that can be converted to PFAAs in the environment and in the human body.

The best studied PFAAs are PFOS and PFOA, although considerable information is available for some other PFAS, including PFNA, PFHxS, PFBA, PFBS, and the GenX chemical HFPO-DA. Laboratory animal toxicology studies and human epidemiological studies suggest health effects that may occur as a result of long-term exposure to PFOA and PFOS at environmentally relevant levels. Figure 7-1 summarizes current health effects information, the references for which are discussed in this section. The other PFAS mentioned above cause generally similar effects in animal studies, with toxicity generally occurring at higher doses for the short-chain PFAAs than for long-chain PFAAs. These health effects, discussed in more detail in Sections 7.1.3, and 7.1.4 are the basis for current guidance values and regulations for PFOA, PFOS, and several other PFAS. These are available in the Water and Soil Regulatory and Guidance Values Table Excel file.



- Animal
  - ☐ Liver effects
  - ☐ Immunological effects
  - ☐ Developmental effects
  - ☐ Endocrine effects (thyroid)
  - ☐ Reproductive effects
  - ☐ Tumors (liver, testicular*, pancreatic)

* PFOA Only

- Human (associations)
  - ☐ Liver effects (increased serum enzymes)
  - ☐ Increased serum cholesterol
  - ☐ Immunological effects (decreased vaccination response)
  - ☐ Developmental effects (decreased birth weight)
  - ☐ Endocrine effects (thyroid disease)
  - ☐ Cardiovascular effects (pregnancy induced hypertension)
  - ☐ Cancer* (testicular, kidney)

Figure 7-1. Some health effects of PFOA and/or PFOS identified from published studies (not exhaustive).

USEPA has finalized its toxicity assessments for the following PFAS:

- the GenX chemicals (USEPA 2021)
- PFBS (USEPA 2021)
- PFBA (USEPA 2022)
- Perfluoropropanoic acid (PFPrA)(USEPA 2023)
- Lithium bis[(trifluoromethyl)sulfonyl]azanide (HQ-115)(USEPA 2023)
- PFHxA (USEPA 2023)

As of August 2023, draft IRIS assessments were available for the following PFAS:

- PFHxS (USEPA 2023)
- PFDA (USEPA 2023)

The IRIS assessment of PFNA is under development.

USEPA (USEPA 2021; 2021) developed draft updated toxicity assessment for PFOA and PFOS which were used as the basis for the updated PFOA and PFOS interim drinking water Health Advisories (USEPA 2022; 2022). The USEPA (2021) also made a final regulatory determination to establish drinking water standards (maximum contaminant levels, MCLs) for PFOA and PFOS and proposed these standards in 2023 (USEPA 2023). As part of this effort, the draft updates of the USEPA toxicity evaluations for PFOA (USEPA 2021) and PFOS (USEPA 2021) were reviewed by the USEPA Science Advisory Board (SAB) (USEPA Science Advisory Board 2022). In response to input from the SAB, the USEPA (2021)) draft toxicity assessment for PFOA and PFOS was revised (USEPA 2023; 2023), and the revised draft assessment were used as the basis of the proposed USEPA (2023) MCLs for PFOA and PFOS.

Much of the information presented here is recent, and new studies continue to become available. Additionally, it should be noted that it was not possible to include all relevant citations, particularly for those compounds with large health effects data sets. Further information on the topics in this section can be found in databases such as the National Library of Medicine’s PubMed (a database containing citations to relevant peer-reviewed publications), and in reviews such as Kirk et al. (2018) and Lau (2012), and in several chapters of the Agency for Toxic Substances and Disease Registry (ATSDR) toxicological profile (ATSDR 2021); DeWitt (2015), and NICNAS (2018) for PFAS in general. Some references for specific PFAS are included in this list:

- PFOA: Australia Government DOH (2018); USEPA (2016); USEPA (2016); NJDWQI (2017) NJDWQI (2017); USEPA (2023)
- PFOS: USEPA (2016); USEPA (2016); MDH (2019); NJDWQI (2018); USEPA (2023)
- PFNA: NJDWQI (2015)

- PFBS: MDH (2022); USEPA (2021)
- PFBA: USEPA (2021); MDH (2018)
- PFHxS: MDH (2020)
- PFHxA: MDH(2021) and USEPA (2022)
- GenX chemicals: RIVM (2016), Chemours (posted online by NC DEQ (2018)); and USEPA (2021)
- Short-chain PFAAs: Buck (2015) and Danish EPA (2015)
- PFECAs: Buck (2015); NJDEP (2021)

Human biomonitoring and sources of exposure are addressed in Section 7.1.1. Information on serum levels of long-chain PFAAs from communities with contaminated drinking water is presented in Table 17-6. The unique toxicokinetic properties of PFAS are discussed in Section 7.1.2. Table 17-7 summarizes available data on PFAS elimination half-lives in humans and experimental animals. The numerous reviews of potential epidemiological associations of health endpoints with PFAAs are discussed in Section 7.1.3. Toxicology studies in mammalian species are summarized in Section 7.1.4, and more detailed toxicology information is presented in Section 17.2.5 and Table 17-8 Toxicological Effects Excel file (last updated November 2021). Section 7.1.5 discusses PFAS mixtures. Section 7.1.6 includes information about using new approach methodologies for evaluating PFAS. Section 7.1.7 provides information about regulating PFAS as a class. Section 7.1.8 includes information about PFAS inhalation toxicity, and Section 7.1.9 includes data gaps and research needs.

7.1.1 Human Biomonitoring and Sources of Exposure

Numerous human biomonitoring studies (CDC 2022; Olsen et al. 2017) have demonstrated that certain PFAS, particularly long-chain PFAAs, are present in the blood serum of most U.S. residents. Long-chain PFAAs, with half-lives of one to several years, are slowly excreted in humans. Therefore, serum levels are indicators of long-term exposure to long-chain PFAAs and do not fluctuate greatly with short-term variations in exposure. Serum PFAA concentrations originate from direct exposure to the compounds and from metabolism of precursor compounds to PFAAs within the body (reviewed in Kudo (2015)). The largest U.S. general population biomonitoring studies are from the National Health and Nutrition Examination Survey (NHANES), a nationally representative survey conducted by the Centers for Disease Control and Prevention (CDC), which began monitoring for PFAS in 1999–2000 (Figure 7-2). As can be seen in Figure 7-2, serum PFAS levels in the general population have declined over time, most notably for PFOS. The most recent NHANES monitoring data (2017–2018) includes eight PFAAs (PFOA, PFOS, PFNA, PFHxS, PFHxA, PFDA, PFUnDA, PFHpS) and four other PFAS (GenX, ADONA, 9-Chlorohexadecafluoro-3-oxanonane-1-sulfonic acid, MeFOSAA); five additional PFAS (PFBS, PFHpA, PFDoDA, PFOSA, EtFOSAA) that were infrequently detected in earlier rounds of NHANES were not monitored in 2017–2018 (CDC 2022). Other adult U.S. general population biomonitoring data come from four studies of blood donors in 2000–2015 (Olsen et al. 2017) and the California Environmental Contaminant Biomonitoring Program (CA OEHHA 2011).

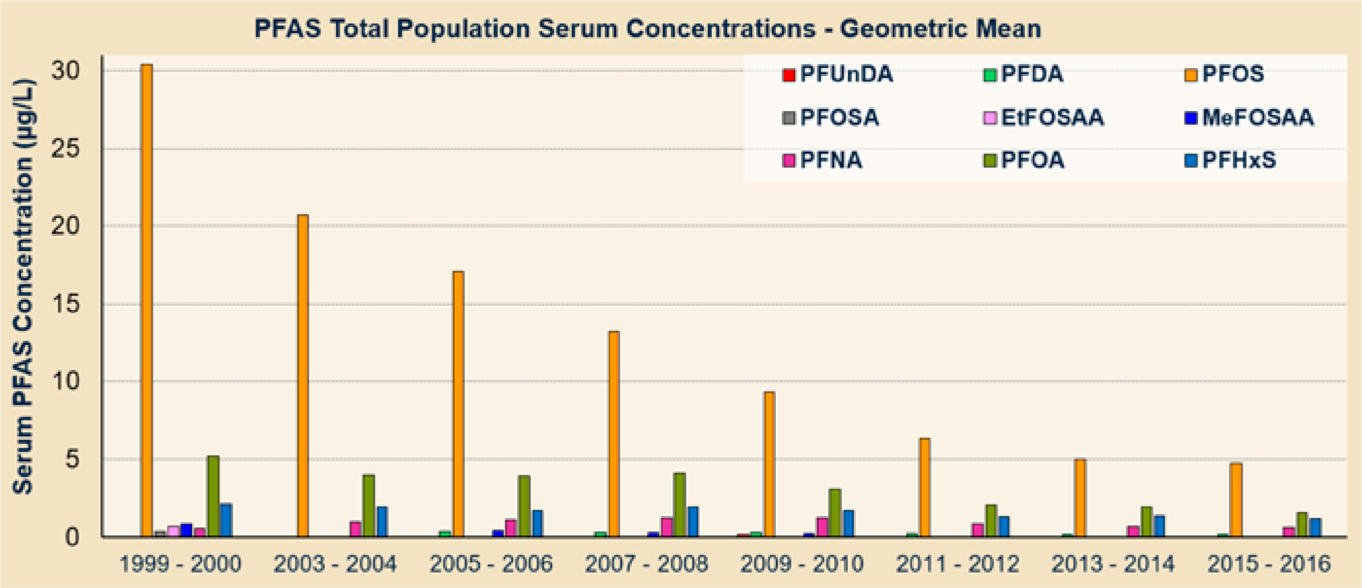


Figure 7-2. Geometric mean serum concentrations (ng/ml) of selected PFAAs (NHANES, 1999-2016).

In the general population, where this is no specific source of PFAS contamination and PFAA concentrations in drinking water and serum are in the typical “background” range, the primary sources of exposure to PFAAs and their precursors appear to be food and food packaging, and consumer products (particularly nonpolymer aftermarket treatments and coatings; Section 2.5), and house dust formed from such consumer products (Trudel et al. 2008; Fromme et al. 2009; Vestergren and Cousins 2009; Beesoon et al. 2012; Gebbink, Berger, and Cousins 2015). PFAS have been detected in air (ATSDR 2021), and inhalation is therefore an additional potential exposure pathway. Serum levels of PFOS and PFOA documented by NHANES data appear to indicate that the phaseout of production and use of these chemicals in most products has resulted in decreased PFOS and PFOA exposures for the general population from these sources. As this occurs, the relative contribution from drinking water to these PFAAs will increase (where they are present in the drinking water).

In communities near sources of PFAS contamination, exposures that are higher than those in the general population can result from ingestion of contaminated drinking water or consumption of fish from contaminated waters. As PFAS concentrations in drinking water increase, the contribution of drinking water to the total body burden increases and typically dominates an individual’s exposure. Information on serum levels of long-chain PFAAs from communities with contaminated drinking water in several U.S. states and other nations is found in Table 17-6. Finally, occupational exposures to workers (for example, in fluoropolymer manufacturing facilities) can be higher than exposures from environmental media.

Specific considerations and exposure routes relevant to PFAS exposures in the fetus, breast-fed and formula-fed infants, and young children are discussed in Section 17.2. Also see Section 17.2.2 for additional discussion of human biomonitoring and sources of human exposure.

7.1.2 Toxicokinetics

Toxicokinetics refers to the absorption, distribution, metabolism, and excretion of toxic substances. PFAAs and some other types of PFAS discussed herein have unique toxicokinetic properties as compared to other types of persistent organic pollutants (POPs). Unlike most other bioaccumulative organic compounds (for example, dioxins, PCBs), PFAAs do not have a high affinity for adipose tissue (fat). In contrast, PFAAs are water soluble, have an affinity for proteins, and generally distribute primarily to the liver and blood serum (Bischel et al. 2011; Lau 2012, 2015; Kato, Ye, and Calafat 2015). Some PFAAs have also been found in kidney, bone, lung, brain, and other organs in laboratory animals and/or limited human studies (Bogdanska et al. 2011; Perez et al. 2013; reviewed in USEPA 2023). PFAAs, GenX chemicals, and ADONA are not metabolized (meaning they do not break down to other PFAS). However, some PFAS that are PFAA precursors (for example, fluorotelomer alcohols, Section 17.2.5.2) can be metabolized to PFAAs within the body.

Table 17-7 summarizes available data on PFAS elimination half-lives (the half-life is the length of time it takes for half of the chemical to be eliminated from the body) in humans and experimental animals. In general, short-chain PFAS are excreted more rapidly than longer chain PFAS in humans and other mammalian species. As discussed in more detail in Section 17.2.3, the excretion rates (for example, elimination half-lives) for specific PFAS can vary substantially between species, and in some cases between males and females of the same species. Half-lives in laboratory animals (rodents and nonhuman primates) generally range from hours to several months for long-chain PFAS, and hours to several days for short-chain PFAS. Human half-lives for PFAS are longer than in other mammalian species, with estimates of several years for long-chain PFAAs and several days to one month for shorter chain PFAAs such as PFBA, PFHxA, and PFBS. Because of the much longer human half-lives, animal-to-human comparisons must account for the much higher internal dose (for example, blood serum level) in humans than in animals from the same administered dose.

Toxicokinetics relevant to developmental exposures to PFAAs are important because developmental effects are considered to be sensitive endpoints for toxicity of long-chain PFAAs, and some human studies have found associations of long-chain PFAAs with decreased fetal growth. PFAAs cross the placenta (reviewed in Lau (2012) and Kudo (2015)) and are present in breast milk (Luebker et al. 2005; White et al. 2009; Kato, Ye, and Calafat 2015), and long-chain PFAAs have been found in cord blood, for example, (Wang et al. 2019), and amniotic fluid (Stein et al. 2012; Zhang et al. 2013). In human infants, exposures from breast milk result in substantial increases in long-chain PFAA serum levels during the first months after birth (Fromme et al. 2010; Mogensen et al. 2015). Due to the higher rate of fluid consumption by infants versus older individuals (USEPA 2019), exposures to infants from formula prepared with PFAS-contaminated water are also higher.

Toxicokinetic factors called clearance factors represent the volume of blood from which a substance is removed per unit time (L/kg/day). Clearance factors have been used to relate external doses (ng/kg/day) of PFOA and PFOS to steady-state serum levels (ng/L). When combined with average water ingestion rates (USEPA 2023), these clearance factors have been used to predict that the expected average increases in the levels of PFAS in blood serum from long-term drinking water exposure are at least 100-fold higher than the concentration in the drinking water (Bartell 2017; NJDWQI 2017; Post, Gleason, and Cooper 2017). See Section 17.2.3.2 for more detail. Bartell (2017), Lu and Bartell (2020), and ATSDR (2022) have developed online calculators that provide estimates of an individual's serum concentrations of PFOA, PFOS, PFNA, and PFHxS from the information that is entered, including drinking water levels of these PFAS and other relevant factors. It should be noted that these estimates are based on long-term exposure to a constant drinking water concentration and that serum PFAS concentrations are impacted by interindividual variability in both toxicokinetic factors (for example, PFAS half-lives) and the daily drinking water ingestion rate.

Finally, toxicokinetics in rodents (Loveless et al. 2006; De Silva et al. 2009) and humans (Zhang et al. 2013; Gao et al. 2015; Beesoon et al. 2011) may differ among isomers of the same PFAA.

See Section 17.2.3 for additional discussion of PFAS excretion and excretion rates, toxicokinetics relative to developmental exposure, the relationship of human exposure to serum levels, and isomer-specific toxicokinetics.

7.1.3 Human Epidemiology Studies

The epidemiological database for long-chain PFAAs, particularly PFOA and PFOS, is more extensive than for many other environmental contaminants. Many of the studies are recent, and the number of available studies is continually increasing. USEPA (2023) identified over 400 human epidemiology studies of PFOA and/or PFOS from searches of the following databases through February, 2022: Pub Med (National Library of Medicine); Web of Science (Thomson Reuters); ToxLine (incorporated into PubMed post 2019); and TSCATS (Toxic Substances Control Act Test Submissions). Many of these studies also evaluated other long-chain PFAAs and/or other PFAS. Some effects, such as changes in serum lipids, liver biomarkers, uric acid levels, thyroid endpoints, vaccine response, and fetal growth, have been evaluated in multiple studies and populations, while only one or a few studies were located for some other effects

These studies can be categorized based on the type of population evaluated: general population, communities with contaminated drinking water, or occupationally exposed workers. Almost all of these studies were published after 2009, with the exception of a small number of occupational studies from a few years prior to that time.

Although discussion of individual epidemiological studies is beyond the scope of this section and the corresponding appendix section, evidence for associations and/or causality for some PFAAs and certain health effects (for example, increased cholesterol, increased liver enzymes, decreased vaccine response, thyroid disease, and for PFOA, some types of cancer) has been evaluated by various academic researchers and government agencies. USEPA (2023; 2023) has concluded that the noncancer human health effects with the strongest evidence for association with PFOA and PFOS are increased serum cholesterol, increased serum alanine aminotransferase (ALT; a marker of liver damage), decreased vaccine response, and decreased birth weight. USEPA (2023) has also concluded that PFOA is linked to testicular and kidney cancer in humans. The conclusions of some of these evaluations are discussed briefly below, with additional detail provided in Section 17.2.4.

For some health endpoints, including increased serum cholesterol, there is general consensus for consistent evidence for association with one or more long-chain PFAAs. Conclusions differ among evaluations by different groups of scientists for other endpoints, noting that the earlier evaluations considered fewer studies than the more recent evaluations. For additional endpoints, data are too limited to make a conclusion, results are inconsistent, or there is no evidence for an association. The general reviews cited in Section 17.2.4 include detailed discussions of epidemiological data for PFOA, PFOS, and PFNA.

As shown in Figure 7-1, associations in human epidemiological studies of PFAAs (primarily PFOA and PFOS) for some endpoints (for example, increased liver enzymes, decreased fetal growth, decreased vaccine response) are consistent with animal toxicology studies (Section 7.1.4). For serum lipids (for example, cholesterol), observations of decreased cholesterol in rodents in some studies, while cholesterol is increased in humans, may result from the higher fat content in the diets of humans as compared to the diet used in most laboratory animal studies and/or large differences in the exposure levels in human versus animal studies (Tan et al. 2013; Rebholz et al. 2016 ; NJDWQI 2017; USEPA 2023).

Associations of some health endpoints with certain PFAAs are generally, although not totally, consistent, and some evaluations have concluded that the data for certain effects support multiple criteria for causality. Historically, risk-based toxicity factors (reference doses for noncancer effects and slope factors for cancer risk) developed by most government agencies are based on dose-response relationships from animal data, with the human data used to support the hazard identification component of toxicity factor development. One factor that has precluded the use of human data in the dose-response component of toxicity factor development is the concurrent exposure to multiple PFAAs in most or all study populations. Because serum levels of co-occurring PFAAs tend to correlate with each other, special modeling approaches must be used to determine the dose-response relationship for individual PFAAs, and the use of these approaches is currently increasing. That fact notwithstanding, Hölzer, Lilienthal, and Schümann (2021) and Schümann, Lilienthal, and Hölzer (2021) developed Human Biomonitoring Values (serum levels below which adverse effects are not expected) and the European Food Safety Authority (EFSA 2020) developed a Tolerable Weekly Intakes (TWI) of 4.4 ng/kg body weight for the sum of four PFAS (PFOA, PFOS, PFNA, and PFHxS) in food based on human data for decreased vaccine response from the general population. These values are lower than many of the values that are based on toxicity data from animals. More recently, California EPA and USEPA have developed draft reference doses for PFOA and PFOS (CA OEHHA 2023; USEPA 2023; 2023), as well as for PFHxS (USEPA 2023) and PFDA (USEPA 2023), and a draft cancer slope factor for PFOA (USEPA 2023; CA OEHHA 2023) based on human general population data that are far below current values based on animal data.

The National Academies of Science, Engineering, and Medicine (NASEM 2022), at the request of ATSDR and the National Institute of Environmental Health Sciences (NIEHS), developed recommendations for testing for PFAS exposure and clinical monitoring for exposed individuals. ATSDR will consider these recommendations in updating its guidance to clinicians regarding PFAS. As part of its work, NASEM (2022) developed “strength of evidence” determinations based on human data for a variety of health effects that are collectively applicable to the total serum concentration of the seven PFAS (PFOA, PFOS, PFHxS, PFNA, PFDA, PFUnDA, and methyl-perfluorooctane sulfonamide [MeFOSA]) currently included in the CDC’s National Report on Human Exposure to Environmental Chemicals (CDC 2022). The NASEM relied on risk-based assessments conducted by EFSA (2020) and the German Human Biomonitoring Commission (2016), (2018) to identify PFAS levels in serum or plasma to inform clinical care. The NASEM determined that: (1) adverse health effects related to PFAS exposure are not expected at PFAS serum levels less than 2 ng/mL; (2) there is a potential for adverse effects, especially in sensitive populations, for PFAS serum levels between 2 and 20 ng/mL; and (3) there is an increased risk of adverse effects for PFAS serum levels above 20 ng/ml. The NASEM recommended PFAS exposure reduction—if a source has been identified—for the two highest categories of PFAS serum concentrations. NASEM (2022) further recommended that clinicians should “offer PFAS [blood] testing to patients likely to have a history of elevated exposure,” including those with potential occupational exposure and those who have lived in communities with known or potential PFAS contamination. The NASEM also recommended that clinicians conduct health screening for several health conditions when the sum of the seven PFAS in serum exceeds the recommended benchmarks. Also see the discussion of the NASEM document in Section 7.1.8, Regulation of PFAS as a Class.

See Section 17.2.4 for additional discussion of epidemiologic studies that have been conducted on PFAS.

7.1.4 Animal Toxicology Studies

This section focuses on the most notable toxicological effects in mammalian studies of certain PFCAs, PFSAs, and PFECAs. All PFAS covered in this section for which data are available cause increased liver weight; additional effects common to some of these PFAS include immune system, hematological (blood cell), and developmental toxicity, as well as more severe types of liver toxicity. Of the four PFAS that have been tested for carcinogenicity in rodents, PFOA, PFOS, and the GenX chemical HFPO-DA caused tumors while PFHxA did not.

In general, toxicity is dependent on both intrinsic potency of the compound (Gomis et al. 2018) and its toxicokinetics. Longer chain PFAAs are generally toxic at lower administered doses than shorter chain compounds because their slower excretion results in a higher internal dose from the same administered dose. Similarly, for those PFAS that are excreted much more rapidly in female rats than in males (Section 7.1.2 and Table 17-7), higher doses in females than in males are needed to achieve the same internal dose.

Toxicological data from animal studies are used as the basis for many human health toxicity factors (for example, reference doses, cancer slope factors) for PFAS. However, as noted above, both California and the USEPA have based recent draft reference doses and/or cancer slope factors for on human data. Certain European toxicity factors are also based on human data (Section 7.1.3) (also see Sections 8.3 and 9.1). Unlike most other environmental contaminants, PFAS have been associated with health effects in humans at much lower exposure levels than the doses used in animal toxicology studies.

Table 17-8 Toxicological Effects Excel file provides information on toxicological effects in mammalian species (hazard identification information) for the following PFAS:

- PFCAs including PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnA, and PFDoA
- PFSAs including PFBS, PFPeS, PFHxS, PFHpS, and PFOS
- PFECAs including ADONA and the GenX chemical HFPO-DA.

Section 17.2.5.1 also summarizes information on systemic effects; reproductive and developmental effects, and chronic toxicity and tumorigenicity of these PFAS.

- Largest publicly available toxicological data sets for: PFOA and PFOS
- Considerable data for: PFBA, PFHxA, PFNA, PFDA, PFBS, and the GenX chemicals HFPO-DA and its ammonium salt
- One or a few studies for: PFHpA, PFUnA, PFDoA, PFHxS, and ADONA
- No toxicological data were located for PFPeA, PFTrDA, PFTeDA, PFPeS, PFHpS, PFNS, or PFDS.

Most toxicological studies of PFAS have been conducted in rats and mice, with a few studies in nonhuman primates (monkeys) and other species such as rabbits.

The National Toxicology Program (NTP 2019; NTP 2019) has conducted 28-day studies of seven PFAS (PFHxA, PFOA, PFNA, PFDA, PFBS, PFHxS, PFOS) in male and female rats that evaluated numerous toxicological endpoints and provided serum PFAA data for each dosed group; results of these studies are included in Table 17-8 Toxicological Effects Excel file. Although the doses at which effects occurred are not provided in this section or in the supporting appendix material, it is emphasized that No Observed Adverse Effect Level (NOAELs) and Lowest Observed Adverse Effect Level (LOAELs) vary widely between compounds for a given endpoint, between different endpoints for the same compound, and between species (and sexes in some cases) for the same compound and endpoint. Furthermore, the effects noted may not have been observed in all studies in which they were evaluated.

NTP (2020) has also conducted a chronic carcinogenicity study of PFOA administered in feed to rats that assessed the contribution of combined gestational and lactational (perinatal) exposure as compared to exposure beginning after weaning. It was concluded that there was clear evidence of carcinogenic activity in male rats based on the increased incidence of liver tumors and pancreatic acinar cell tumors, and some evidence of carcinogenic activity in female rats based on increased incidence of pancreatic acinar cell tumors. Non-neoplastic lesions were increased in the liver and pancreas in males and in the liver, kidney, forestomach and thyroid in females. There were very few significant differences in effects when exposure began in the perinatal period compared to when it began after weaning.

See Section 17.2.5.1 for additional discussion of studies in animals that have evaluated the effects of these PFAS on noncancer and cancer endpoints.

There is increasing awareness and interest in potential human exposure to PFAS other than the PFAAs and the PFECAs, GenX and ADONA, that are discussed in Section 17.2.5.1. These include ether and polyether PFAS, dicarboxylic acid polyether PFAS, fluorotelomer alcohols, and fluorotelomer sulfonic acids. Information relevant to health effects of these additional PFAS is discussed in Section 17.2.6.1.

7.1.5 PFAS Mixtures

This section provides a summary of current toxicity-based approaches for addressing mixtures of PFAS and currently available information on toxicity of PFAS mixtures. This is an active area of research. Additional information is presented in Section 17.2.

Although humans are generally exposed to mixtures of PFAS, relatively few studies of the toxicity of PFAS mixtures, including defined mixtures (i.e., mixtures for which the identities and concentrations of the components are known) or complex mixtures (i.e., mixtures for which the identities and concentrations of the components are not fully characterized) such as AFFF, were located; they are summarized in Section 17.2.7.2. These include in vitro studies of nuclear receptor activation in cultured cells transfected with the receptor of interest, and toxicity in cultured cells; in vivo studies in zebrafish (a model species for human toxicity) and mammalian species; and epidemiologic studies of a population exposed to AFFF in drinking water.

7.1.5.1 Approaches for Assessing Toxicity of PFAS Mixtures

Multiple PFAS are present in the blood serum of almost all U.S. residents (Section 7.1.1), and PFAS often occur as mixtures of individual chemicals in the environment (for example, drinking water, fish, soil, and air). Therefore, approaches to assess the toxicity of PFAS mixtures are needed. Development of approaches for consideration of the health effects of mixtures of PFAS is a priority for USEPA, ATSDR, and other U.S. federal agencies, as discussed at a recent National Academy of Sciences (NAS) workshop on federal research on human health effects of PFAS (NAS 2021), and USEPA (2023) developed a draft framework for evaluation of non-cancer risk of PFAS mixtures that was reviewed by the USEPA Science Advisory Board (2022). Approaches to assessing the toxicity of PFAS mixtures have also been the subject of several peer-reviewed publications (discussed below), including Peters and Gonzalez (2011), Bil et al. (2021), Cousins et al. (2020), and Goodrum et al. (2021). However, as discussed at the NAS workshop, relevant data on several aspects of this topic are limited. For example, there is a lack of information on in vivo and in vitro toxicity of PFAS mixtures, as well as on health effects in human populations when exposure to multiple PFAS has occurred (NAS 2021).

As is the case for mixtures of environmental contaminants in general, the toxicity of PFAS mixtures can be evaluated through studies of defined or undefined mixtures (mixtures of known concentrations of individual PFAS or complex mixtures that may include both known and unidentified PFAS, respectively). The small database of currently available toxicity studies of PFAS mixtures is summarized in Section 17.2. These include a few studies of the undefined PFAS mixtures found in AFFF and a limited number of studies of defined PFAS mixtures, including in vitro studies of nuclear receptor activation in transfected cultured cells, and toxicity studies in cultured cells and zebrafish. Notably, no rodent or primate studies of defined mixtures of PFAS were located. When evaluating exposure and health effects for PFAS mixtures in drinking water or other media, it must be emphasized that identification of the PFAS that are present is dependent both on the composition of the mixture and the suite of PFAS detected by the analytical method that was used (McDonough et al. 2019). Methods currently used for routine analysis are described in Section 11.2. Additional analytical methods (for example, nontarget analysis) that are primarily used in research studies can identify numerous additional PFAS not currently included in standard methods.

As discussed in USEPA and ATSDR guidance for risk assessment of mixtures (USEPA 1986; USEPA 2000; ATSDR 2018), toxicological interactions among components of a mixture may include dose additivity, response additivity, synergism, and antagonism. Dose additivity is based on the assumption that the chemicals in the mixture have the same mode of action (MOA) and cause the same effects, and differ only in potency. The components are assumed to have similarly shaped dose-response curves, and the effect caused by the mixture is assumed to be the sum of the effects caused by each of the individual chemicals present. Because MOA information for PFAS is incomplete, the draft USEPA (2023) framework for evaluation of risks of PFAS mixtures assumes dose additivity based on similarity of toxicological endpoint/health effects without requiring a common MOA. Response additivity is based on the assumption that the toxic effect of a mixture can be predicted by summing the doses of each chemical in the mixture (relative to each chemical’s critical effect dose) such that the contribution from each chemical to the overall effect of the mixture is not influenced by the other chemicals. For example, when assuming additivity, the sum of the incremental cancer risks of multiple individual co-occurring carcinogens can be used to estimate the total cancer risk of the mixture. Toxicological interactions of components of mixtures may also be synergistic (greater than additive) or antagonistic (less than additive), resulting in larger or smaller effects than would occur with dose additivity or response additivity.

As discussed in this section, currently available toxicological information for PFAS does not clearly support a specific approach for conducting risk assessments of PFAS mixtures. While the toxicological effects of many PFAS are generally similar, the most sensitive toxicological endpoints may vary among PFAS. Additionally, multiple MOAs for PFAS toxicity are likely; these MOAs appear to be complex, and currently are not well understood. Furthermore, the MOA for a specific PFAS may not be the same for all effects (for example, hepatic toxicity, developmental toxicity), and a specific effect may not occur through the same MOA for all PFAS (for example, different MOAs for liver toxicity of PFOA and PFOS; Peters and Gonzalez 2011; NAS 2021). In the limited number of studies of PFAS mixtures, additive, synergistic, and antagonistic interactions among PFAS have been observed. As noted by Wolf et al. (2014), toxicological interactions of PFAS are dependent on the identities and concentrations of the PFAS in the mixture, the biological model, and the endpoint being evaluated (see Section 17.2).

Some regulatory agencies consider the cumulative toxicity of PFAS that co-occur in environmental media, while other agencies consider PFAS individually as required by their regulatory process and/or the scientific uncertainty as to whether co-occurring PFAS are sufficiently similar to consider them as a group. Several approaches that have been proposed to address the toxicity of PFAS mixtures are discussed in Section 17.2.7.1. The goal of these approaches is to facilitate the risk assessment of PFAS mixtures detected at contaminated sites and to develop health-protective guidelines that potentially account for the combined effects of multiple PFAS. Some general approaches for assessing the cumulative effects of exposure to PFAS, as related to site risk assessment, are discussed in Section 9.1.3.1. Examples of the application of such approaches to PFAS are reviewed by Cousins et al. (2020), who also provided a “summary of existing or proposed grouping approaches based on the sum of various PFAS in drinking water.” Most of the approaches that have been proposed assume dose additivity, although scientific uncertainties are associated with this assumption, as discussed above and in Section 17.2.7.1.

7.1.5.2 Toxicology Studies of PFAS Mixtures

The relatively few studies of the toxicity of defined mixtures of PFAS that were located are summarized in Section 17.2.7.2. These include in vitro studies of nuclear receptor activation in cultured cells transfected with the receptor of interest, toxicity in cultured cells and zebrafish (a model species for human toxicity), and a few mammalian studies.

7.1.6 Evaluating PFAS using New Approach Methodologies

Traditional toxicity testing methods using in vivo mammalian models are time-, cost-, and labor-intensive. As noted in Section 17.2.8, including Table 17-8 Toxicological Effects Excel file, mammalian (most commonly rodent) toxicity information is available for only a relatively small group of PFAS, including a number of long- and short-chain PFCAs and PFSAs, certain fluorotelomer alcohols and fluorotelomer sulfonates, and several of the per- and polyfluoroether replacements, with PFOS and PFOA having the most extensive data sets. Under current USEPA risk assessment guidelines used by most states, in vivo mammalian laboratory animal or human data are required for development of chemical-specific toxicity factors (for example, reference doses) used as the basis for standards and guidance values for PFAS in drinking water and other environmental media. It is therefore important that in vivo mammalian data continue to be made available for those PFAS with a high level of public health concern, such as those detected at elevated concentrations in drinking water. However, in vivo mammalian studies are not feasible for all of the individual PFAS, of which there are thousands (USEPA 2020). Additionally, USEPA aims to refine and reduce the use of mammalian species in toxicology testing and to use non-animal testing methods when appropriate. With the goal of rapidly generating toxicity, MOA, toxicokinetic, and exposure information on PFAS and reducing the use of mammalian species in testing, the USEPA is collaborating with the National Toxicology Program (NTP) of the National Institutes of Environmental Health Sciences through the REACT (Responsive Evaluation and Assessment of Chemical Toxicity) Program. New Approach Methodologies, such as rapid toxicity assays in cultured cells and zebrafish, in silico (computational) approaches, and high throughput exposure modeling are being developed and used with the goal of generating data that will inform toxicology and risk assessment of PFAS (Patlewicz et al. 2019; USEPA 2019, 2019). More information on this effort is provided in Section 17.2.8.

7.1.7 Regulation of PFAS as a Class

Recent estimates could have the total number of individual PFAS at more than 12,000 (see Section 2 and USEPA 2020). Although not all of these PFAS are commercially important, more than 3,000 individual PFAS have been found in European commerce (OECD 2018), and approximately 4,700 PFAS are in the current global marketplace (Cousins et al. 2020). Of these, Buck et al. (2021) reported that 256 PFAS are commercially relevant on a global basis. Fewer than 20 PFAS are well-studied toxicologically (all of which are nonpolymer PFAS), and all of those that have been studied have been found to be capable of causing adverse effects in animals and/or humans (Sections 7.1, 7.2, and 17.2).

Because substantial time and resources are required to adequately characterize the chemical and physical properties and potential adverse effects of an individual chemical (for example, NTP, 2022), the conclusion that it is neither feasible nor health-protective to follow the “chemical-by-chemical” regulatory paradigm for PFAS has gained increasing acceptance. Beginning with the Helsingør Statement (Scheringer et al. 2014) and continuing with the Madrid Statement (Blum et al. 2015) and Zurich Statement (Ritscher et al. 2018), groups of scientists and others have called for the coordinated regulation of all PFAS, citing their persistence, widespread use, and frequent lack of toxicity data, among other concerns. The FluoroCouncil (Bowman 2015) took issue with the Madrid Statement (Blum et al. 2015) for failing to acknowledge the fact that “fluorotechnology is essential technology,” and for ignoring scientific information that indicates differences in persistence and toxicity between long- and short-chain PFAAs and the efforts of industry to limit environmental impacts of PFAS.

One of the various regulatory strategies proposed by Blum et al. (2015), Ritscher et al. (2018), and subsequently by Cousins et al. (2019), is to limit ongoing uses of PFAS to those PFAS deemed to be “essential.” Cousins et al. (2019) proposed that essential uses of PFAS are those “uses considered essential because they are necessary for health and safety or other highly important purposes and for which alternatives have not been established.” Examples of essential uses are certain medical devices and occupational protective clothing (Cousins et al. 2019). The European Commission (2020)[2800] developed a strategy to phase out the use of PFAS in the European Union “unless it is proven essential for society.” Similarly, while noting that “a ban on all PFAS as a group is neither practical, necessary, nor achievable,” the Royal Society of Chemistry (2021)[] supported the concept of essential use for those PFAS defined as “vital or highly desirable by wider society.” Other publications have also supported the concept of “essential use” as a regulatory strategy for PFAS (Kwiatkowski et al. 2020; Dean et al. 2020), with Gluge et al. (2022) describing the information requirements and analyses necessary to regulate PFAS under the concept of essential use.

Kwiatkowski et al. (2020) also emphasized the importance of eliminating nonessential uses of PFAS as an example of a class-based approach to PFAS regulation. Other class-based regulatory strategies cited by Kwiatkowski et al. (2020) include banning PFAS in certain product categories; prioritizing research and development funding for treatment and disposal/destruction methods that are targeted to (and effective for) PFAS as a class; and development of class-based cleanup standards so that all PFAS—not just a few—are remediated.

7.1.7.1 Grouping Strategies

The Zurich Statement (Ritscher et al. 2018) and others (Cousins et al. 2020; Anderson et al. 2022) have considered the utility of and strategies for grouping PFAS for more effective regulation, as distinct from treating all PFAS as a single class. Cousins et al. (2020) offered a number of potential bases for grouping PFAS, with the selected method depending on whether the intended action is to regulate based on intrinsic properties or to inform risk assessment. Each of the proposed grouping methods has different data requirements, advantages, and disadvantages (see Cousins et al. 2020). Examples of the grouping methods proposed by Cousins et al. (2020) are summarized in Table 7-1.

Table 7-1. Grouping approaches for PFAS (excerpted and adapted from Cousins et al. 2020, CC BY-NC 3.0).

	Individual approaches	**PFAS grouped**	**Data requirements**
Approaches based on intrinsic properties	P-sufficient approach[1]	All PFAS	None
	According to PBT/vPvB[2]	PFAS that are bioaccumulative	Bioaccumulation potential
	According to PMT/vPvM[2]	PFAS that are mobile in water	Water solubility
	Polymers of low concern (PLC)	Some fluoropolymers	Polymer composition, molecular weight, other properties
Approaches that inform risk assessment	Arrowhead[3]	Specific PFAAs and precursors	Degradation schemes
	Total organofluorine	Extractable or adsorbable PFAS	None
	Simple additive toxicity	2-20 PFAS, currently primarily PFAAs	Toxicity
	Relative potency factor	Multiple PFAAs	Toxicity, potency, toxicokinetics
	Grouping PFAS with similar adverse effects, mode of action, toxicokinetic	Limited PFAAs	Toxicity, mode of action, toxicokinetics

[1] P-sufficient = grouping based on the persistence of perfluoroalkyls and on the formation of perfluoroalkyls as stable end products of precursor polyfluoroalkyls.[2] PBT = persistent, bioaccumulative, toxic; vPvB = very persistent and very bioaccumulative; PMT = persistent, mobile, and toxic; vPvM = very persistent and very mobile.

[3] Arrowhead = “when a representative PFAS, usually a PFAA, is managed together with its salts and precursors.”

As described in its National PFAS Testing Strategy, the USEPA (2021) is working to understand the impacts of different categories of PFAS, in part to identify which PFAS will require testing under the Toxic Substances Control Act authority. The PFAS categorization will also support the prioritization of individual PFAS or “classes” of PFAS for additional research on human exposure or toxicity. The USEPA’s categorization of PFAS is based on similarities in structure, physical-chemical properties, and toxicological properties. The USEPA plans to use these categories for hazard assessment and to support risk-based decision making and will also develop categories of PFAS based on removal technologies. The USEPA will draw on information from both of these approaches to prioritize research.

Anderson et al. (2022) considered several options for grouping of PFAS for the purpose of protecting human health from drinking water exposure and assessing risks of PFAS mixtures. No single grouping strategy was identified that was “sufficient” for all regulatory or public health risk assessment purposes. However, the study authors generally supported the conclusions that: “Not all PFAS should be grouped together, persistence alone is not sufficient for the purposes of assessing health risk, and that the nature and definition of the subgroups can only be defined on a situation-dependent and case-by-case manner” (Anderson et al. 2022).

A recent review of the properties of fluoroplastics and fluoroelastomer—two types of fluoropolymer—concluded that based on their high molecular weight, lack of biological availability, and other physical and chemical properties, these PFAS are a distinct group of PFAS that “should not be grouped with other PFAS for hazard assessment or regulatory purposes” (Korzeniowski et al. 2022).

California’s Department of Toxic Substances (DTSC) regulates PFAS as a class by prohibiting the sale of select consumer products if the product contains any PFAS and an Alternatives Analysis has determined that there are viable replacements. Supported by specific California laws that define environmental persistence and toxicity as hazard traits warranting regulation, the DTSC considers that (1) all PFAS or their degradation, reaction, or metabolic products are environmentally persistent, and (2) “nearly all” PFAS exhibit other hazard traits as defined by California law, including toxicity (Balan et al. 2021). PFAS-containing product categories that DTSC has identified for regulation include (1) carpets and rugs with perfluoroalkyl or polyfluoroalkyl substances, (2) treatments containing perfluoroalkyl or polyfluoroalkyl substances for use on converted textiles or leathers, such as carpets, upholstery, clothing, and shoes, and (3) plant fiber–based food packaging containing perfluoroalkyl or polyfluoroalkyl substances (https://dtsc.ca.gov/scp/). In August 2022, California’s legislature banned the use of any PFAS “intentionally added” to a cosmetic product manufactured, sold, or delivered into the state of California. The text of the legislation cites the “highly toxic” and “highly persistent” “class of chemicals known as PFAS” (California Assembly 2022).

The National Academies of Science, Engineering, and Medicine (NASEM 2022) developed “strength of evidence” determinations collectively applicable to the seven PFAS currently included in the CDC’s National Report on Human Exposure to Environmental Chemicals (CDC 2022) for each health effect that they considered, while recognizing that differences exist among these PFAS. Specifically, the NASEM (2022) stated: “Most people are exposed to mixtures of PFAS such that specific effects are difficult to disentangle. Considering these issues, and recognizing that some PFAS are infrequently measured, the committee provided one strength-of-evidence determination for all PFAS for each health effect, recognizing that providing one conclusion across PFAS may not account for the distinct physical, chemical, and toxicological properties of each type of PFAS.”

The European Chemicals Agency (ECHA) proposed to restrict all per- and polyfluoroalkyl substances with a single regulation (ECHA 2023). The proposed regulation cites concerns that “all PFAS” are “very persistent” in the environment and may adversely affect the health of humans and the environment. ECHA (2023) observed that if the proposal is put into effect, it would prevent the release of around 4.4 million tons of PFAS over a 30-year period.

In February 2023, Health Canada proposed to regulate all PFAS in drinking water that can be quantified with U.S. EPA Method 533, Method 537.1, or both. The sum of total detectable PFAS will be required to be no more than 30 ng/L, based on potential health effects from exposure to this group of PFAS in drinking water (Health Canada 2023).

7.1.8 PFAS Inhalation Toxicity

This section provides an overview of available information on inhalation exposure and toxicity of PFAS. While exposure to PFAS via inhalation can potentially occur both outdoors and indoors, most of the exposure studies that were identified focused on residential and nonresidential indoor environments. A review by Savvaides et al. (2021) reported that, in the available studies, the profile of PFAS detected in indoor air varied in different indoor environments and in different seasons of the year in the same location.

In general, inhalation exposure considerations differ for ionized (negatively charged) PFAS [(for example, PFAAs such as PFOA and PFOS, and perfluoroether carboxylates such as HPFO-DA, which have low volatility and occur primarily in indoor (for example, house) dust], as compared to neutral PFAS [(for example, FTOHs, FOSAs, and FOSEs), which are much more volatile and tend to occur in the vapor phase] (Table 4-1; De Silva et al. 2021). For this reason, the negatively charged and neutral PFAS are discussed in separate sections below. For example, Shoeib et al. (2011) and Ericson Jogsten et al. (2012) reported that PFAAs and neutral PFAS were both found in residential environments. However, the concentration of neutral PFAS was higher than PFAAs in residential indoor air while the concentration of PFAAs in house dust was higher than neutral PFAS. Furthermore, Gustafsson et al. (2022) reported that the total concentration of PFAS and the distribution of specific PFAS varied in different size fractions of house dust. The highest total PFAS concentration was found in the smallest particles, which represent the respirable fraction, while PFCAs were highest in the largest and smallest particles, with lower concentrations in the intermediate-size particles. Information about media-specific occurrence studies is included in Section 6.

Some neutral PFAS are “precursors” (i.e., PFAS that can be metabolized or otherwise degraded to form terminally stable PFAAs), so that inhalation exposure to PFAAs may occur both through “direct” and “indirect” pathways. For example, Gomis et al. (2016) characterized the contribution of “direct” exposure to PFOA and “indirect” exposure to 8:2 FTOH to the total serum PFOA concentrations in ski waxers exposed to PFAS via inhalation, and Chang et al. (2017) reported the metabolism of EtFOSE to PFOS in rats exposed via inhalation.

Although this section does not focus on development of reference concentrations and unit risk factors for inhalation exposure, it is noted that ECOS (2023) provides information on inhalation toxicity factors for PFAS that have been developed by some states. In general, inhalation toxicity studies that can be used to develop toxicity factors are not available for PFAS, and these inhalation toxicity factors are based on oral toxicity data and route-to-route (oral-to-inhalation) extrapolation; a recent publication (Monnot et al. 2022) supports this approach.

7.1.8.1 Negatively Charged PFAS

As mentioned above, negatively charged PFAS such as PFAAs and perfluoroether carboxylates (for example, HPFO-DA) are not highly volatile. The primary route of occupational exposure to PFAAs is “likely [to be] inhalation of aerosols complexed with airborne dusts,” and elevated serum PFAA levels in occupationally exposed individuals indicates that absorption occurs via inhalation (ATSDR 2021). A major contributor to inhalation exposure to negatively charged PFAS in the general population is indoor dust containing PFAS that originates from consumer products (for example, treated carpets and furniture) and other potential sources; such dust can also contain neutral PFAS (Savvaides et al. 2021). Although exposure to dust can occur through direct ingestion, dust can also be inhaled and then swallowed after being trapped in mucous in the respiratory tract (USEPA 2017). Floor-stripping and waxing were also reported as sources of PFAAs in airborne particulate matter ($PM_{2.0}$; Zhou et al. 2022).

Depending on the individual chemical, there are limited or no laboratory animal data on the inhalation toxicity of negatively charged PFAS, including those with a large number of oral toxicology studies in laboratory animals. For example, ATSDR and/or USEPA toxicity evaluations cite two acute, one short-term, and one developmental rat inhalation study of PFOA (ATSDR 2021; USEPA, 2016), and a single acute rat inhalation study for each of three additional PFAS: PFNA (ATSDR 2021); PFOS (USEPA 2016); and GenX (USEPA 2021). In these inhalation studies, exposure was via aerosols or dust. No additional inhalation studies for PFOA or PFOS were identified in more recent draft USEPA evaluations (USEPA 2023; 2023), and no inhalation toxicity studies were identified by ATSDR (2021) for PFBA, PFHxA, PFHpA, PFDA, PFUnDA, PFDoDA, PFBS, PFHxS, or PFOS, or by USEPA for PFBS (USEPA 2021), PFBA (USEPA 2022), or PFHxA (USEPA 2023).

In toxicokinetic studies, PFOA was detected in the blood serum of rats after inhalation exposure via aerosols (Hinderliter 2003; Hinderliter, DeLorme, and Kennedy 2006). However, little data are available on extent of absorption for inhalation vs. oral exposure, and an analysis by the Michigan Department of Environmental Quality (MI DEQ 2018) of PFOA data from Hinderliter, DeLorme, and Kennedy (2006) demonstrated that the relative extent of absorption from inhalation versus oral exposure was not constant over the concentration range in the study. Inhalation exposure to PFOA, PFOS, and PFNA caused systemic effects similar to oral exposure, including hepatic toxicity (PFOA–Kennedy et al. 1986; Staples et al. 1984; PFNA–Kinney, Chromey, and Kennedy 1989; PFOS–Rusch, Rinehart, and Bozak 1979) and decreased neonatal body weight after gestational exposure (Staples et al. 1984). Nasal and/or eye irritation, and/or respiratory effects, were also reported from acute exposure to relatively high concentrations of PFOA (Rusch 1979; Griffith and Long 1980; Kennedy et al. 1986), PFNA (Kinney, Chromey, and Kennedy 1989), PFOS (Rusch, Rinehart, and Bozak 1979), and GenX (DuPont 2009).

7.1.8.2 Neutral PFAS

Neutral PFAS such as FTOHs, FOSA, and FOSE are more volatile than negatively charged PFAS. They have been found in the vapor phase in indoor environments, including residences, classrooms and offices, outdoor gear/apparel and carpet stores, and ski waxing facilities (Shoeib et al. 2011; Morales-McDevitt 2021; Gomis et al. 2016), and inhalation can be a primary human exposure route (De Silva et al. 2021). Furthermore, Titaley et al. (2022) reported high concentrations of neutral PFAS in AFFF and predicted that vapor intrusion of these PFAS will occur from AFFF-contaminated groundwater.

The toxicokinetics of 6:2 FTOH and 8:2 FTOH in rats were reported to be similar after inhalation and oral exposure, including systemic absorption and the profile of metabolites formed (Himmelstein et al. 2012). As discussed in Section 17.2.6.2, metabolites of FTOHs include terminal PFCAs (for example, formation of PFHpA, PFOA, and PFNA from 8:2 FTOH), as well as persistent toxic metabolites in some cases (for example, 5:3 FTA from 6:2 FTOH) (Kabadi et al. 2020). Although no inhalation toxicology studies of FTOHs in laboratory animals were identified, the similarity in inhalation and oral toxicokinetics, including metabolite profiles, suggests that systemic toxicity is likely similar from both exposure routes. Similarly, although no inhalation toxicity studies of FOSA or EtFOSE were identified, FOSA was reported to be metabolized to PFOS in humans believed to be exposed through inhalation (Olsen et al. 2005) and EtFOSE was metabolized to PFOS in rats (Chang et al. 2017).

7.1.9 Data Gaps and Research Needs

Although many studies relevant to health effects of PFAAs have become available in the last few years, important data gaps remain for most of the PFAAs and PFECAs discussed here and in Section 17.2, as well as for many additional PFAS used in commerce or found in AFFF. The data gaps (discussed in more detail in Section 17.2.9) include:

- Human half-lives and other toxicokinetic data are not available for some PFAS found in drinking water and other environmental media.
- Currently available data indicate that reactive intermediates may form in the body from the metabolism of PFAA precursors to PFAAs. More studies are needed to understand the toxicologic significance of these intermediates.
- Data on absorption and toxicity of PFAS via dermal contact and inhalation are very limited, and more studies to characterize these exposure routes are needed.
- There are relatively few epidemiological studies of communities exposed to AFFF, PFOS, and/or other PFAS in drinking water. Although a number of studies of associations of PFAS with a variety of health effects have recently been reported for populations exposed to AFFF-contaminated drinking water in Sweden (Section 17.2.4), more such studies from other locations are needed.
- Additional toxicology data are needed for some PFAAs found in environmental media, including drinking water. In particular, very little toxicologic data are available for PFHpA, and no information was located for PFPeA.
- There is also a need for additional toxicological studies on the effects of PFAS mixtures in that although humans are exposed to multiple PFAS, information on toxicological interactions of PFAS is limited.
- Multigenerational studies of the reproductive and developmental effects of additional PFAS are needed.
- Chronic toxicity and carcinogenicity studies are currently available for only four PFAS (PFHxA, PFOA, PFOS, GenX), and are needed for PFHxS, PFNA, ADONA, and other PFAS to which humans may be exposed.
- The majority of the many thousands of PFAS, including those in commercial use, have very limited or no toxicity data. This is a critical data gap in health effects information for PFAS.
- Similarly, current NHANES biomonitoring in blood serum includes only 11 PFAS, primarily PFAAs, and breast milk biomonitoring data for these PFAS are limited. There is limited or no biomonitoring data in blood serum or breast milk for many other PFAS produced or used in the United States, some of which are known to be bioaccumulative in humans.
- Information on PFAS in powdered and prepared infant formula are extremely limited. Monitoring data for formula are needed to understand this potentially important source of exposure to infants.
- Little is known about how racial or socioeconomic differences may affect susceptibility to the adverse effects of PFAS exposure. Studies are needed to address this.

7.2 Ecological Toxicology

This section is organized around currently available toxicity information for invertebrates (aquatic/benthic/terrestrial), vertebrates (fish, birds, reptiles/amphibians, mammals), and plants. Toxicological data can be obtained from a general literature review as well as by querying of the USEPA Ecotox Database (USEPA 2023). As discussed below, this is an active area of research, and interested readers are encouraged to query the literature for updated research and reviews, such as the Environmental Toxicology and Chemistry Special Issue on Understanding Environmental Risk from Exposure to Per- and Polyfluoroalkyl Substances (PFAS; Vol 40, Issue 3, March 2021 https://setac.onlinelibrary.wiley.com/toc/15528618/2021/40/3); Argonne 2021; Zodrow et al. 2021; and Divine et al. 2020. There are also much data available for PFOS and PFOA toxicity that were used to derive the USEPA's draft Aquatic Life Ambient Water Quality Criteria (US EPA 2022).

It is important to note that this section is not intended to represent an exhaustive review of PFAS ecological toxicology (referred to herein as "ecotoxicity") studies. Ecotoxicity of PFAS is an area of active research, with new information emerging regularly. Toxicological effects of apical endpoints presented and discussed herein are generally those considered most relevant to ecological communities—mainly survival, growth, and reproduction. Both acute and chronic exposure studies are discussed in this section. Although data have been generated for other toxicological endpoints, these studies are not the focus of this section, but may occasionally be referenced. Application of these data in ecological risk assessment is discussed in Section 9.2

7.2.1 Introduction

Biomonitoring studies across a variety of organisms, habitats, and geographies show that certain PFAS can accumulate in wildlife and that exposures are occurring on a global scale (Reiner and Place 2015; Giesy and Kannan 2001[]). Therefore, it is important to understand how PFAS exposure and bioaccumulation may manifest in adverse effects, particularly as these effects relate to ecological communities. Information on bioaccumulation of PFAS is addressed in Section 6.5. This section provides an overview of resources available and some published toxicological data relating exposure of PFAS to toxic effects on aquatic, benthic, and terrestrial organisms, with the goal of broadening the reader's understanding of known or potential effects in ecological systems, as well as highlighting areas where more data are needed. This information can also be applied for use in ecological risk assessments (ERAs), particularly because the ecological risk of PFAS is currently neither well understood nor uniformly assessed or regulated. However, the reader is encouraged to review the primary source literature from which cited ecotoxicity values have been derived to confirm and understand the basis and assumptions of the cited literature before using information obtained from this section in an ERA.

This review shows that ecotoxicity data are available for certain PFAS, particularly for PFOA and PFOS, with most studies focused to date on aquatic invertebrates. Although there are numerous studies on PFAS exposure in terrestrial vertebrates (for example, mammals, reptiles, birds), and ample toxicological studies in laboratory animals, there is, overall, relatively little to no ecologically relevant toxicity data for terrestrial vertebrates in the wild (though this is currently being investigated for avian receptors; see SERDP ER22-3202, https://serdp-estcp.org). Although some mechanistic studies have been conducted with aquatic organisms, little has been done with other organisms and even less has been done with different classes of PFAS in aquatic and terrestrial wildlife. However, see research funded under SERDP's Statement of Need (SON): Improved Understanding of the Ecotoxicity of Mixtures of Per- and Polyfluoroalkyl Substances (ERSON-22-C1) for projects investigating mechanisms of PFAS toxicity and accumulation in aquatic and terrestrial receptors.

The focus of most ecotoxicity studies to date has been primarily on PFOS and PFOA. Therefore, most of the data discussed and summarized in this section are for those two compounds. However, data for other PFAS, including short-chain PFAS and precursors (Section 2.2), are also presented where available. Given the historical differences among older analytical methods and more recent advances in analyzing PFAS, the focus of the ecotoxicity studies covered in this review is generally on those published from approximately the year 2000 and later.

In general, single-chemical PFAS exposure studies indicate that the sensitivity of invertebrates to PFAS exposure can be chemical-specific and vary by organism and environmental factors (for example, see Lewis et al. 2022). Published studies of the toxicity of PFAS mixtures are available (Section 17.2.7.2), but the understanding of PFAS mixtures toxicity remains uncertain at this time. Risk assessment implications of exposure to mixtures are discussed further in Section 9.2.1.3. There is a paucity of field studies for avian and mammalian wildlife species, and confounding factors such as the co-occurrence of other stressors (other pollutants, physical stressors, etc.) makes it difficult to definitively associate PFAS exposure with adverse outcomes (Custer 2021). There are a handful of avian studies on multiple species that investigate egg hatching outcomes and potential correlations to PFAS exposures (Custer et al. 2014; Groffen et al. 2019; Tartu et al. 2014), and field-based effects studies on mammals are difficult to find (ECCC 2018). However, laboratory animal studies (see Section 7.1) suggest potential relationships between PFAS tissue concentrations and immunological, hematological, liver, kidney, and reproductive effects (DeWitt 2015; ECCC 2018).

Data from biomonitoring studies (see Section 5.5) indicate that PFAS exposure is occurring in wildlife; however, the lack of toxicity data for this group of organisms represents a significant data gap. This highlights the need for additional study of this class of compounds in general, as well as the need for expansion of toxicity studies to a larger group of PFAS and to a greater variety of taxa, and for field studies that may assess population-level effects.

Relative aquatic toxicity for PFAS is discussed in the following sections using descriptive criteria developed by the USEPA within their Design for the Environment Program for the Alternatives Assessments and the Safer Choice Program (USEPA 2011[]; USEPA 2015). These criteria are expressed as relative toxicity based on effects concentrations ranging from less than 0.1 mg/L (very high toxicity) to greater than 100 mg/L (low toxicity); criteria are provided in Table 7-2.

Table 7-2. Aquatic toxicity classification criteria (USEPA 2011) (in mg constituent/L water)

Toxicity	**Very High**	**High**	**Moderate**	**Low**	**Very Low**
USEPA: Aquatic Toxicity (Acute, LC_{50})	<1.0	1–10	>10–100	>100	NA
USEPA: Aquatic Toxicity (Chronic, LOEC)	<0.1	0.1–1	>1–10	>10	NA

7.2.2 Invertebrates

7.2.2.1 Aquatic

Aquatic invertebrates may be exposed to PFAS by direct contact with PFAS in the water column, as well as via the diet, including trophic transfer and particle ingestion. There are more toxicity data available for PFOS than for other PFAS. PFAS have a very wide range of toxicities to aquatic organisms under acute exposure scenarios following the USEPA Hazard Criteria (Table 7-2), but overall, they would be classified as having moderate to low toxicity to invertebrates. One exception with this generalization is that of mussel exposures to PFOS and PFOA in the marine environment, where no effect was seen at 0.00001 mg/L but a LOEC was reported at 0.0001 mg/L (Fabbri et al. 2014); this would result in classification as a very high hazard using the USEPA Hazard Criteria. With the current body of literature, the sensitivity of marine invertebrates to PFOS and PFOA appears equivocal.

Given that PFAS are persistent pollutants, chronic exposure scenarios are most relevant for aquatic receptors. Importantly, compared to acute studies, there are relatively few chronic studies in aquatic invertebrates. Most chronic effects data are for PFOS and PFOA. Life cycle tests with multiple taxa have been conducted to evaluate the chronic toxicity of PFOS to freshwater aquatic invertebrates. The chironomid (*Chironomus tentans*) is currently reported as having the greatest sensitivity to chronic exposure, with reduced total emergence reported at 0.0023 mg PFOS/L (MacDonald et al. 2004). More recent studies, including McCarthy et al. (2021), show impairment on survival in the chironomid (*C. dilutus*) at even lower concentrations, with EC10 and EC20 values in 20-day tests for PFOS at 1.4 and 1.7 ug/L, respectively. Studies by Bots et al. (2010) and Van Gossum et al. (2009) indicated that damselflies (*Enallagma cyathigerum*) may also be similarly sensitive to PFOS, with NOEC and LOEC values of 0.01 and 0.1 mg/L, respectively. In the marine environment, a life cycle toxicity test with the saltwater mysid (Mysidopsis bahia) yielded a NOEC of 0.24 mg PFOS/L based on growth and number of young produced (Drottar and Krueger 2000).

Some PFAS may potentially cause adverse effects in aquatic invertebrates that span across multiple generations. Marziali et al. (2019) evaluated generational effects in chironomids (*C. riparius*); each generation was exposed to a nominal concentration of 0.01 mg/L of PFOA, PFOS, and PFBS; all treatments showed reduced growth in at least several generations, with no observed induced tolerance to the studied PFAS. However, potential effects at the population level were not demonstrated in this study based on similar population growth rates between treatments and controls, suggesting that toxicity risk to an ecosystem is unlikely (Marziali et al. 2019).

Benthic Organisms and Sediment Toxicity
Toxicity to benthic (sediment-dwelling) organisms is generally the result of exposure to the chemical in overlying water, sediment, and porewater, including trophic transfer and sediment particle ingestion (Zareitalabad et al. 2013). There are relatively few published sediment toxicity studies on PFAS exposure to benthic invertebrates compared to those for aquatic invertebrates. The UK Environment Agency (2004)[] provided a freshwater sediment screening value of 0.0067 mg/kg (wet weight), based upon a predicted no-effect concentration (PNEC) of 2.5 µg/L and a river sediment K_d of 8.7 L/kg. Note, however, that sediment screening values based on K_d may not be applicable across all sites. Section 9.2 (Ecological Risk Assessment) discusses application of K_d in deriving sediment screening values.

Additionally, Bakke et al. (2010) provided PFOS concentration ranges for marine sediment quality classified as background, good, moderate, bad, and very bad. The PFOS threshold for “good” sediment, for which no toxic effects are expected, was reported as 0.22 mg/kg. This value, however, is based on an aquatic PNEC of 72 µg/L derived from a limited data set and an unspecified Kd value, and thus is not a reliable concentration with which to predict toxic effects. More recently, Simpson et al. (2021) conducted a multimedia acute and chronic study on a variety of marine/estuarine invertebrates (including an amphipod, a copepod, a crab, and two species of bivalve) that included PFOS-spiked sediment toxicity tests. Simpson et al. (2021) found that PFOS significantly decreased survival and/or reproduction for the amphipod (Melita plumulosa) at sediment concentrations of 29 mg/kg or greater. Although they did not identify a relationship between toxicity and PFOS concentrations in sediment, they observed a strong relationship among toxicity, organic carbon content of sediments, and dissolved PFOS concentrations in the overlying water of the test vessel. These results suggested that the dissolved fraction of PFOS in water is likely a key contributor to sediment toxicity. Based on sediment concentrations normalized to 1% organic carbon (1%OC), the authors derived an LC10 of 132 mg/kg (1%OC) and LC50 of 150 mg/kg (1%OC) for PFOS, and EC10, EC20, and EC50 of 21, 35, and 89 mg/kg (1%OC), respectively, for reproductive effects (Simpson et al. 2021). The focus of Simpson et al. (2021) was on the amphipod, but this publication also provided data for additional marine species. The authors also developed sediment thresholds using Kd and species sensitivity distributions from water exposures.

Laboratory-controlled freshwater and marine sediment toxicity tests for PFAS are sparse. With so few studies available and with variability in test organisms and testing methods, it is difficult to define PFAS toxicity thresholds for benthic organisms or to determine if benthic organisms are similarly sensitive to PFAS compared to other aquatic invertebrates. However, benthic organism toxicity thresholds do not need to be limited to just invertebrates, as shown by Simpson et al. (2021), who developed PFOS thresholds from a species sensitivity distribution (SSD) generated from published data on other types of species using a K_d approach.

7.2.2.2 Terrestrial Invertebrates

Compared to aquatic invertebrates, there are fewer studies on the effects of PFAS on terrestrial invertebrates (i.e., invertebrates living in terrestrial habitats). Brignole et al. (2003), whose study was summarized in Beach et al. (2006), summarized results of acute oral and dermal studies of PFOS conducted on the honeybee (*Apis melifera*), although the dose was reported in terms of mass of PFOS per bee, which may not be relevant for evaluating ecological risks. However, these studies, when converted to a dose per kilogram of food (2 mg PFOS per kg sugar solution), suggested that PFOS was “highly toxic” to honeybees, as defined by the International Commission for Bee Botany. Mommaerts et al. (2011) identified in a chronic oral dosing study on the bumblebee (*Bombus terrestris*) an LC50 of 1.01 mg PFOS/L sugar water and noted that PFOS exposure caused detrimental reproductive effects (decreased ovarian size).

Effects on fecundity from exposure to various PFAS have been shown to carry down through multiple generations in the roundworm (*Caenorhabditis elegans)*. Tominaga et al. (2004) conducted a multigenerational study in *C. elegans* exposed to PFOA, PFOS, and PFNA, finding that concentrations orders of magnitude lower than those causing lethality decreased worm abundance, and that effects were observed even in the fourth generation. Other studies have evaluated the mechanisms of PFAS toxicity. Xu et al. (2013) indicated that exposure to PFOS induced oxidative stress and DNA damage in the earthworm, *Eisenia fetida*. Stylianou et al. (2019) evaluated food chain transfer of PFOS-treated *Escherichia coli* to *C. elegans* and noted distinct gene expression profiles associated with development, innate immunity, and stress response.

With regard to soil invertebrate toxicity testing, studies (while few in number) suggest a low to moderate toxicity of PFOS and PFOA, with toxicity generally occurring on a parts per million scale. These studies have mainly focused on the earthworm *Eisenia fetida*. Sindermann et al. (2002) conducted a 14-day chronic soil study on *E. fetida* with PFOS and identified a NOEC of 77 mg PFOS/kg soil, a LOEC of 141 mg/kg, and an LD50 of 373 mg/kg. Other chronic earthworm studies indicated toxic concentrations of a similar magnitude, with LC50s ranging from 84 mg/kg–447 mg/kg (Mayilswami et al. 2014; Zareitalabad et al. 2013). The Norwegian Pollution Control Authority NPCA (2006), as reported in Danish Ministry of the Environment (2015), conducted acute soil toxicity tests in *E. fetida*, looking at reproductive endpoints for PFOA, PFOS, and the short-chain 6:2 fluorotelomer sulfonate (6:2 FTS). Results of this study indicated that, overall, the evaluated PFAS exhibited a moderate-high toxicity. Reproductive effects (decreased number of cocoons, decreased hatchability, and decreased number and weight of juveniles) for PFOS and PFOA were noted. 6:2 FTS toxicity was found to be less than that for either PFOS or PFOA in the same study. Karnjanapiboonwong et al. (2018) conducted a 21-day soil study with *E. fetida* on bioaccumulation, mortality, and weight loss with PFBS, PFHxS, PFNA, and PFHpA and generally observed no effects at soil concentrations below 100 mg/kg in comparison with the controls. Importantly, the authors report tissue concentrations following exposures to PFBS, PFHxS, PFNA and PFHpA thus indicating potential for trophic transfer from soil to higher level organisms (Karnjanapiboonwong et al. 2018).

The limited amount of terrestrial invertebrate data presents a data gap; additional toxicity studies are needed to better characterize ecotoxicological effects in this group of organisms. Additionally, it will be important to understand how field/soil conditions (for example, organic carbon content, pH, etc.) may influence toxicity. For example, Princz et al. (2018) found that PFOS toxicity for two different species of soil invertebrates was approximately two to four times greater when organisms were tested on sandy loam versus clay loam soils.

7.2.3 Vertebrates

The following sections describe available toxicity data for vertebrate species, including fish, amphibians/reptiles, birds, and mammalian wildlife.

7.2.3.1 Fish

Acute freshwater LC50 values based on survival for PFOS range from 7.8 to 22 mg/L for Rainbow trout (*Oncorhynchus mykiss*), to 9.1 mg/L for fathead minnow (*Pimephales promelas*) (Robertson 1986; Palmer, Van Hoven and Krueger 2002).

There are relatively few chronic PFOS studies in fish, but (Drottar and Krueger (2000)) calculated a chronic NOAEL based on early life stage mortality in Pimephales promelas to be 0.29 mg/L. Palmer, Van Hoven and Krueger (2002) also calculated an acute NOAEL of 6.3 mg/L for *Oncorhynchus mykiss*. Saltwater acute values based on survival for *Oncorhynchus mykiss* were calculated to be 13.7 mg/L.

Other than PFOS, there are limited aquatic ecotoxicity data for other PFAS. Within the summary data presented here, acute exposure durations were for 6 days. One study was noted that investigated the chronic toxicity of PFNA following a 180-day exposure; the LOEC ranged from 0.01-1 mg/L depending on the endpoint (Zheng et al. 2011).

7.2.3.2 Amphibians/Reptiles

There are relatively limited toxicity data available for PFAS effects on amphibians, including several studies on various species of frogs; no studies on reptiles were found in the literature search. The data available for PFOS and PFOA show a wide range of effects-based concentrations.

More amphibian data are available for PFOS in comparison to other PFAS, and indicate mortality generally tends to occur at levels of 10 mg/L or higher, whereas nonlethal effects (for example, growth; EC10) may occur at approximately 1–2 mg/L (that is, moderate to high toxicity) or lower (Ankley et al. 2004; Yang et al. 2014; Fort et al. 2019). However, more recent studies suggest chronic toxicity may occur at levels lower than 1 mg/L. Flynn et al. (2019), for example, found a 72-day LOEC in the American bullfrog (*Lithobates catesbeiana*) of 0.29 mg/L based on developmental effects (reduction in snout vent length).

Ankley et al. (2004) conducted a 5-week study on PFOS toxicity in the northern leopard frog (*Rana pipiens*) and observed that LC50s decreased with increasing test duration time; LC50s ranged from 12.5 mg/L at 1 week to 6.2 mg/L at 5 weeks. This study also anecdotally noted the presence of kinked tails, as well as a delayed time to initial metamorphosis and differences in limb bud and foot paddle emergence in the 1, 3, and 10 mg/L groups. A PFOS study, based on a 3M study reported in OECD (2002) on another frog species, African clawed frog (*Xenopus laevis*), suggested toxicity at concentrations of similar magnitude to those observed in the Ankley study, and identified inhibition of growth and malformation during development.

PFAS exposure has also been shown to affect the thyroid, and hence development, in amphibians (for example, Cheng et al. 2011; Flynn et al. 2022). A study by Cheng et al. (2011) that exposed African clawed frog (*X. laevis*) tadpoles to PFOS at concentrations ranging from 0.1 to 100 ug/L in water found up-regulation of several thyroid hormone–regulated genes, suggesting possible thyroid disruption. Flynn et al. (2022) conducted a chronic study that evaluated sublethal developmental effects on *R. pipiens*, the American toad (*Anaxyrus americanus*), and the eastern tiger salamander (*Ambystoma tigrinum*), following exposure up to 30 days to 10, 100, and 1,000 ug/L of PFOS, PFOA, PFHxS, and 6:2 FTS). They found a LOEC of 10 ug/L based on reduced body mass for all four PFAS in anurans, and PFOA, PFHxS, and 6:2 FTS in the salamander.

Amphibian studies suggest that PFOS may be less toxic than certain other PFAS (Yang et al. 2014 and Abercrombie et al. 2021) Brown, Flynn, and Hoverman (2021) found increased trematode infection in the northern leopard frog resulting from exposure to 0.01 mg/L PFHxS, whereas no effect was observed for PFOS (however, no such effect was noted in the higher PFHxS treatment dose of 0.1 mg/L; the authors postulated that this could potentially be due to adverse effects of PFHxS to the trematode itself).

Many of the older amphibian studies focused on early life aquatic exposures. More recent studies suggest that amphibians may be even more sensitive to PFAS if one looks at later life stages; nonlethal effects other than survival; growth and reproduction; terrestrial exposure routes; or multiple exposure media. Abercrombie et al. (2021) indicated LOECs ranging from 0.05-0.12 mg/L for a toad, frog, and salamander exposed to PFOS, PFOA, or PFHxS in a soil substrate. Flynn et al. (2021) found enhanced PFOS and PFOA toxicity in a spiked sediment outdoor mesocosm study, suggesting that evaluating only aquatic exposures may underestimate toxicity from exposure to PFAS in multiple media, which is more representative of actual field conditions.

7.2.3.3 Birds

There are currently a limited number of published laboratory studies available that address PFAS toxicity in avian wildlife species (Newsted et al. 2006; Newsted et al. 2005; Newsted et al. 2007; Newsted et al. 2008; Dennis et al. 2020; Bursian et al. 2021). The northern bobwhite quail (*Colinus virginianus*) and the mallard duck (*Anas platyrhynchos*) were exposed to PFOS (Newsted et al. 2005; Newsted et al. 2006; Newsted et al. 2007) or PFBS (Newsted et al. 2008) via the diet. The LD50s reported following acute exposure to PFOS are 61 mg/kg-bw/d and 150 mg/kg-bw/d for the northern bobwhite quail and the mallard, respectively (Newsted et al. 2006). In a separate chronic dietary study, Newsted et al. (2007) found that a feed concentration of 10 mg PFOS/kg resulted in an average daily intake (ADI) LOAEL of 0.77 mg/kg-bw/d based on increased liver weight in female quail. A feed concentration rate of 50 mg/kg resulted in an ADI LOAEL of 6.4 mg/kg-bw/d based on lethality in mallards (Newsted et al. 2007).

More recent avian studies on the northern bobwhite (Dennis et al. 2020) and Japanese quail (*Coturnix japonica*) (Bursian et al. 2021) evaluated dietary effects of PFOS, PFOA, PFHxS, and the AFFF formulations from 3M and Ansul. Bursian et al. (2021) estimated average daily doses causing 50% mortality (ADD50) at 5 days' exposure ranging from 38 mg/kg-d for PFOS (≥98% chemical grade) to 130 mg/kg-d for PFOS in feed spiked with 3M AFFF, which is a product formulation that is a mixture of fluorinated and other compounds (LC50 of 351–467 mg/kg of feed, respectively). More information about AFFF is included in Section 3. This subacute study also evaluated effects resulting from a mixture of PFOS and PFOA; the authors suggested that these results showed potential additive effects, and a relative potency of PFOA approximately half that of PFOS (Bursian et al. 2021). Dennis et al. (2020) evaluated chronic toxicity associated with PFOS and a mixture of PFOS and PFHxS in drinking water on the northern bobwhite quail. Reduced body weight in females and impaired hatching success were observed at doses lower than those used in the Newsted study (Newsted et al. 2007), deriving a chronic toxic dose of 0.0031 mg PFOS+ PFHxS/kg-bw/d and 0.00245 mg PFOS/kg-bw/d, respective to the previously mentioned endpoints.

Some egg injection studies suggest exposure to PFOS may adversely affect chick development during incubation. For example, Molina et al. (2006) found that eggs injected with varying doses of PFOS had a lower rate of hatching success and had noted pathological changes in the liver in the leghorn chicken. However, there is some concern regarding the use of these data in risk assessments due to issues related to the method of exposure and other methodological issues that can influence the outcomes of the studies. Although these studies are useful for evaluating mechanisms and creating structure-activity relationships, they may not be appropriate for direct application in risk assessments.

Quail and mallard appear less sensitive to PFBS relative to PFOS. Acute dietary exposure to PFBS resulted in NOAELs of 3,160 and 5,620 mg PFBS/kg-feed for the northern bobwhite quail and mallard, respectively, for the lethal endpoint; these feed concentrations are equivalent to an ADI of 774 mg/kg-bw/d in quail and 2,190 mg/kg-bw/d in mallards (Newsted et al. 2008). A NOAEC for northern bobwhite quail reproduction following chronic dietary exposure to PFBS was reported at 900 mg/kg-feed, equivalent to an ADI of 87.8 mg/kg-bw/d (Newsted et al. 2008).

Although there are few PFAS laboratory toxicity studies for birds, there are even fewer effect-based field studies. Custer et al. (2012) and Custer et al. (2014) evaluated PFOS exposure in tree swallows (*Tachycineta bicolor*), identifying a negative association between PFOS concentration in eggs (~150 ng/g-ww) and hatching success. One issue with the findings as suggested by the authors is that the greatest observed effects on hatching were typically found in areas that likely have co-contamination issues (PCBs, PAHs, mercury); however, the influence of these other contaminants is still not clear. This issue of effects from co-contaminants came to light when Custer et al. (2019) conducted a field study evaluating the effects of PFAS on tree swallows in a more isolated area with known PFAS impacts (Clark's Marsh near the former Wurtsmith Air Force Base, MI); other potential contaminants were at or below regional anthropogenic background levels. This study resulted in mean PFOS egg concentrations of 662 ng/g-ww, and overall hatching success was not impacted. Groffen et al. (2019) conducted a field study in great tits (*Parus major*) near a former fluorochemical plant. They reported median egg concentrations of 48,056 ng/g-ww for PFOS, 18 ng/g-ww for PFOA, and 315 ng/g-ww for PFDS. The authors concluded that reduced hatching success in the birds was associated with a mixture of PFAS (PFOS, PFDS, PFDoDA, PFTrDA, and PFTeDA) (Groffen et al. 2019). Taken together, a linear relationship between PFAS exposure and potential effects in avian species remains uncertain; this highlights the importance of considering co-exposure of common environmental contaminants and

PFAS mixtures when reviewing field studies.

Lastly, indirect effects, such as reduction in a local food source resulting from a PFAS release, may potentially affect bird populations. de Vries et al. (2017), for example, found a decline in abundance of flamingos following a release of fire-fighting foams containing PFOS and other PFAS to a salt lake; the authors postulated that this decline was potentially related to a reduction in prey item abundance due to PFOS toxicity.

7.2.3.4 Mammalian Wildlife

PFAS exposure to wildlife is occurring on a global scale and across a variety of habitats (Reiner and Place 2015; Giesy and Kannan, 2001). Wildlife may accumulate PFAS from direct exposure to air, dust, water, soil, and sediments, as well as through diet. Maternal transfer of PFAS is also a relevant exposure route, as these compounds have been shown to cross the placenta (Gronnestad et al. 2017; Houde et al. 2006). PFAS have also been shown to biomagnify, so higher trophic level predators have higher PFAS levels in tissues compared with prey items (Reiner and Place 2015). Of the PFAS analyzed in wildlife exposure studies, PFOS is the one most frequently detected, and at the highest concentrations, in tissue samples (Reiner and Place 2015). Concentrations in tissue have also been observed to vary with age, sex, and species (DeSilva et al. 2021).

Given the widespread occurrence of PFAS in wildlife, it is important to understand if such exposure manifests in adverse effects and ultimately how exposure may impact wildlife populations. Laboratory animal models show that, in general, PFAS are readily absorbed and distributed among protein-rich tissues (liver, serum, kidney) in mammals, and that certain PFAS (particularly long-chain compounds) have a relatively long half-life in the body. Toxicity tests on laboratory mammals (mice, etc.) have shown that exposure to PFAS may result in adverse effects on the hepatic, endocrine, and immune systems; development; and certain types of cancers, as discussed in Section 7.1.4.

Based on the findings from mammalian toxicity studies in laboratory animals, one might expect to find similar effects in mammalian wildlife (at similar exposure levels). Laboratory studies focusing on growth, reproduction, and survival effects on laboratory mammals provide data to support the development of toxicity reference values for use in ERA of wildlife species. NOAELs and LOAELs can be derived from these studies for use in ERA (as further discussed in Section 9.2, Ecological Risk Assessment), but these values should be used with caution and understanding of their associated uncertainty. Many of these studies may have also included other endpoints, such as systemic or metabolic endpoints, that are not typically used for ERA and may demonstrate effects at lower doses than the growth, reproduction, and survival effects.

Although there are numerous studies evaluating toxicity of PFAS in laboratory animals (as discussed in Section 7.1.4), and there are numerous exposure studies in mammalian wildlife, very few studies have evaluated PFAS toxicity with respect to wildlife exposures. The studies that have been conducted typically evaluated relationships between the concentrations of a small number of PFAS in various protein-rich biological media (for example, blood serum, liver) and expression of select biomarkers. One study on sea otters related concentrations of PFOA and PFOS in liver tissue to health condition and possible immune effects (Kannan, Perotta and Thomas 2006). Table 7-3 summarizes these studies.

Table 7-3. Summary of PFAS toxicity studies in mammalian wildlife

Species	**Summary of Findings**	**Reference**
Sea otter *Enhydra lutris*	Higher PFOS/PFOA concentrations in liver samples found in diseased otters versus nondiseased group	Kannan, Perrotta and Thomas 2006
Bottlenose dolphin *Tursiops truncatus*	Significant positive associations between serum total PFAS concentrations and multiple immunological, hematopoietic, renal, and hepatic function endpoints	Fair et al. 2013
Wood mouse *Apodemus sylvaticus*	Significant positive relationship between liver PFOS concentration and hepatic endpoints (relative liver weight, microsomal lipid peroxidation level); significant negative association with serum alanine aminotransferase (ALT) activity	Hoff et al. 2004
Wild pig *Sus scrofa*	No significant correlation between PFAS liver concentrations and multiple blood, hepatic, and immunological endpoints, whereas significant correlations were observed for other pollutants (for example, dioxin-like compounds, PCBs, organohaline pesticides)	Watanabe et al. 2010

It is important to note that while certain associations have been observed between PFAS concentrations and various immunological, hematopoietic, renal, and hepatic function biomarkers, these associations are not necessarily indicative of actual impairment to an individual organism or within a larger population.

Perhaps one of the biggest challenges with wildlife toxicity studies is that wildlife are exposed to multiple chemical, biological, and physical stressors, making it difficult to determine whether noted effects are directly related to PFAS, to other stressors, or to a combination of stressors. The accumulation of other types of POPs, such as PCBs, dioxins, and pesticides, and metals such as mercury, in wildlife has been well established and, in some studies, correlated body burden to adverse effects. Arctic mammal studies have reported relationships between organohalogen exposure and endocrine disruption, reduced immune function, and adverse effects on the liver and other organs (Letcher et al. 2010). Numerous nonchemical environmental factors such as climate change, habitat loss, and seasonal availability of food may also confound toxicity studies, making it difficult for field studies to discriminate those effects related solely to PFAS. As an example, Watanabe et al. (2010) found no association between PFAS levels and a variety of biomarkers in wild pigs, whereas the study found significant positive associations between these parameters and other types of contaminants (for example, PCBs) that were also detected in liver tissue samples.

Currently, there are few data points available for mammalian wildlife, and the current literature focuses on bioaccumulation and specific endpoints that may not be ecologically relevant, as discussed above. Additionally, bioaccumulation studies have traditionally focused on protein-rich tissues such as liver or blood serum because PFAS preferentially bind to proteins; because PFAS could also be present in other tissues, focus on only a subset of tissues can potentially underestimate the total body burden of PFAS. Thus, exposure cannot be fully characterized from these studies, and pinpointing correlations between target organ or whole-body effects and PFAS exposure is not possible at this point in time. A better understanding of mammalian exposures to the broad spectrum of PFAS, precursor compounds, and mixtures of PFAS, as well as other environmental contaminants, is critical in advancing this field of study. Given the challenges with conducting field studies, this information could be obtained in part through more robust dosing studies in mammals that are representative of various wildlife taxa, and on toxicological endpoints that are directly relevant to population-based effects; however, more field studies are also needed to confirm laboratory models. Groups such as the U.S. Department of Defense's Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) have recently identified such critical data needs (SERDP-ESTCP 2017).

7.2.4 Plants

The following sections describe available toxicity data for aquatic and terrestrial plants.

.

7.2.4.1 Aquatic Plants

Data on the toxic effects of PFAS on aquatic plants are limited, with available studies focusing on PFOS included in USEPA Ecotox Database (USEPA 2023). The acute toxicity (EC50s) of PFOS to aquatic plants (such as *Selanastrum* and *Lemna* species) generally ranges from roughly 31 to 108 parts per million (mg/L), with NOEC values from the same studies being approximately 7–30 mg/L; (Boudreau et al. 2003; Sutherland and Krueger 2001; Drottar and Krueger 2000). Chronic effects (EC50s) were found to be similar to acute values, but varied over a wide range, depending on species and endpoint (2–305 mg/L), with NOECs from the same studies ranging from 0.3 to 11.4 mg/L (Hanson et al. 2005; Boudreau et al. 2003; Desjardins et al. 2001, Desjardins et al. 2001; Desjardins et al. 2001).

7.2.4.2 Terrestrial Plants

There are limited PFAS toxicity data for terrestrial plants; a review of the literature yielded only a few soil phytotoxicity studies. Brignole et al. (2003) evaluated PFOS exposure (21 days) on a variety of crop plants (alfalfa, onion, ryegrass, soybean, tomato, flax, and lettuce) using emergence, survival, and shoot height and weight as endpoints, and demonstrated effects occurring at concentrations ranging from 57 mg/kg to over 1,000 mg/kg. Other studies (Li 2009; Zhao et al. (2011)) conducted on both PFOS and PFOA on multiple crop plants found a wide range of toxicity among species and also observed a range of toxicity within species (specifically, *Brassica rapa chinensis*). The most sensitive species may be *Triticum aestivum* where the 30-day NOEC reported was 1 mg/kg (Zhao et al. 2014). Toxicity may also be moderated by soil characteristics; for example, Zhao et al. (2011) showed that the amount of organic matter in soil significantly influenced toxicity, where higher organic carbon content decreased both accumulation of PFOA and PFOS and phytotoxicity. Additionally, PFAS chain length may affect uptake of PFAS into plant tissue; see Section 5.6 for further discussion.

7.2.5 Uncertainties and Conclusions

This section presented ecotoxicological information with the intent of providing the reader with an overview of the types of organisms and ecotoxicity studies available for PFAS in the current literature (as of 2023). This section also presented available information about the ranges of concentrations of PFAS (notably, PFOS) in soil, sediment, and water that have been associated with adverse effects. In summary, ecotoxicity studies demonstrate a wide range of effects concentrations across the various terrestrial and aquatic biota. In general, aquatic invertebrates appear to be more sensitive to PFOS and other PFAS than their terrestrial counterparts. Differences in species sensitivities, analytical methods, environmental substrate, test conditions, and reproducibility of results make it difficult to generalize overall effects, and some species may be more or less sensitive than others.

Although there are numerous studies on the toxicity of select PFAS to aquatic invertebrates, these studies are generally limited to a very small number of PFAS (typically PFOS, and to a lesser extent, PFOA). Because PFAS represent a broad spectrum of compounds, it is important to expand ecotoxicity studies to evaluate additional PFAS, including short-chain and precursor compounds, as well as “next generation” replacement compounds. Recently, Jones et al. (2022) published a compilation of acute aquatic toxicity following exposures to “next-generation” foams and one reference foam (short-chain PFAS AFFF). Of the 14 species tested, the short-chain PFAS AFFF was least toxic in comparison to the next-generation foams in 11 taxa following acute exposure. In cross-species comparison for the short-chain PFAS AFFF lethality data, the mud snail (*T. obsoleta*) and the freshwater amphipod (*H. azteca*) were the most sensitive, and a variety of amphibian species were the least sensitive (Jones et al. 2022). More data are anticipated from these authors on chronic exposures to a subset of these species with projects funded under the SERDP Statement of Need ERSON-20-A1, which is aimed at quantifying the potential ecotoxicity of fluorine-free surfactant foam formulations (www.serdp-estcp.org). Other studies show that some of the short-chain replacements, such as GenX, are more toxic than PFOS-based foam formulations (Conley et al. 2022).

Importantly, the available studies on foam formulations and individual PFAS exposures indicate a wide range of effects levels for PFAS in aquatic invertebrates, suggesting a level of complexity that has not yet been adequately assessed.

Significantly fewer toxicity studies are available for other groups of aquatic or benthic organisms, and few to no studies are available for avian or mammalian wildlife or plants, presenting a significant gap in our understanding of how the widespread presence of PFAS in the environment may be affecting ecological communities. Additional (or any) data on toxicological endpoints most relevant to community-level effects, such as survival, growth, and reproduction, will be extremely beneficial in understanding potential ecological impacts.

Updated September 2023.

8 Basis of Regulations

The PFAS team developed a Risk Assessment and Regulations training video with content related to this section.

This section describes various federal and state regulatory programs that apply to PFAS. Because state regulations for PFAS in environmental media are changing rapidly, only a few state regulations are summarized in this section, as examples. A PFAS Regulatory Programs Summary Excel file has been developed and is available as an Excel file. ITRC also maintains updated the PFAS Water and Soil Regulatory and Guidance Values Table Excel file, and the PFAS Air Criteria Table Excel file that include information state, federal, and some international countries. This section includes a brief explanation of examples of various health effects and how they are used in the development of regulations and advisories.

Section Number	Topic
8.1	Introduction
8.2	Regulatory Programs
8.3	Differences in the Available Regulations, Advisories, and Guidance

8.1 Introduction

PFAS became contaminants of emerging concern in the early 2000s. In recent years federal, state, and international authorities have established a number of health-based regulatory values and evaluation criteria. As with the case for most emerging contaminants, the regulatory process dealing with PFAS is in various stages of development, and the values and criteria being established vary between individual states, the U.S. government, and international agencies. This section describes examples of various federal and state regulatory programs and includes links to tables that provide established PFAS health-based criteria.

The terms “regulatory” or “regulation” are used in this document to refer to requirements that have gone through a formal process to be promulgated and legally enforceable as identified under local, state, federal, or international programs. The terms “guidance” and “advisory” apply to all other policies and numerical values.

8.2 Regulatory Programs

8.2.1 Background to Regulation of PFAS

The scientific community is rapidly recognizing and evolving its understanding of PFAS in the environment, causing an increased pace of development of guidance values and regulations. the PFAS Water and Soil Regulatory and Guidance Values Table Excel file has been developed and is available as an Excel file. Human health protection is the primary focus of the PFAS regulations, guidance, and advisories developed to date. Regulations and guidance have focused on the PFAAs, precursor compounds, and FECAs. Like many other emerging contaminants, the regulatory and guidance values for PFAS can vary across programs, with differences due to the selection and interpretation of different key toxicity studies, choice of uncertainty factors, and approaches used for animal-to-human extrapolation. The choice of exposure assumptions, including the life stage and the percentage of exposure assumed to come from non-drinking water sources, may also differ. Thus, both differences in scientific conclusions and public health policy choices affect the myriad of regulatory and guidance initiatives for PFAS. More information is included in Section 8.3.

In addition to values that specify health-based concentration limits, agencies have used various strategies to limit the use and release of PFAS. For example, the USEPA worked with the eight primary U.S. PFAS manufacturers and processors to eliminate PFOA and many PFOA precursors and higher homologues by 2015 (USEPA 2017). Additionally, the Organisation for Economic Co-operation and Development OECD (2015) has described various international policies, voluntary initiatives, biomonitoring, and environmental monitoring programs to control PFAS. More information regarding the history of these developments is in Section 2.4.

Authority for regulating PFAS in the United States is derived from a number of federal and state statutes, regulations, and policy initiatives. This section provides a brief overview of the major federal statutes and regulatory programs that govern PFAS.

8.2.2 Federal PFAS Regulations

Within the United States, currently both the USEPA and the FDA have regulatory or guidance initiatives for PFAS. The USEPA has the authority to regulate PFAS under several different statutes as outlined below. To date, USEPA has not yet finalized listing PFAS as hazardous wastes or substances under its available statutory authorities, including the Resource Conservation and Recovery Act (RCRA), Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), Emergency Planning and Community Right-to-Know Act, or the Clean Air Act. USEPA has also not yet finalized regulations for any PFAS under the Safe Drinking Water Act. However, USEPA has now proposed listing PFOS and PFOA as CERCLA hazardous substances (Section 8.2.2.6) and has proposed draft primary drinking water regulations for a number of PFAS (Section 8.2.2.4). The Key Actions to Address PFAS website includes more detailed information about the actions of some of these programs (USEPA 2023). Key Actions to Address PFAS website includes more detailed information about the actions of some of these programs.

Through the Office of Regulatory Affairs, the Office of Management and Budget maintains a list of regulatory actions which have been initiated by the USEPA and certain other federal agencies. That list is updated periodically to give the status of the regulations and is available at https://www.reginfo.gov/public/Forward?SearchTarget=RegReview&textfield=PFAS.

8.2.2.1 National Defense Authorization Act (NDAA)

Through the NDAA, which is enacted early each year, Congress mandates many actions that the Department of Defense (DOD) must comply with, some of them concerning PFAS. At times, separate PFAS-related requirements for the USEPA or other federal entities are also made. Although these activities are not regulatory or guidance in nature, they are important in advancing human health exposure studies of PFAS, remediation of PFAS-contaminated water, development of new technologies to reduce PFAS exposure, interagency collaboration on PFAS, and other PFAS-related actions at the federal level.

The Regulatory Programs Summary Excel file lists by responsible agency the PFAS actions enacted through each NDAA. The NDAA for 2018 was the first one to have a PFAS requirement mandating the Centers for Disease Control and Prevention (CDC) and the Agency for Toxic Substances and Disease Registry (ATSDR) to study PFAS exposure and health implications in communities near current or former military bases and known to have had PFAS in their drinking water, groundwater, or other sources of water. Subsequent NDAAs have had increasing numbers of PFAS-related requirements, as listed on the PFAS Regulatory Programs Summary Excel file.

8.2.2.2 USEPA PFAS Action Plan

USEPA issued a PFAS Action Plan (USEPA 2019) in February 2019 and an update a year later (USEPA 2020). The plan included a discussion about the process for moving forward to establish PFOA and PFOS MCLs for drinking water, and it included a number of main actions that encompassed more than just safe drinking water issues. More information about USEPA's previous actions to address PFAS is available on their website (USEPA 2021). The USEPA (2021) document was superseded by the strategic roadmap described below.

8.2.2.3 USEPA Strategic Roadmap

In October 2021, the USEPA published the *PFAS Strategic Roadmap: EPA's Commitments to Action 2021–2024* (USEPA 2021). The USEPA's stated goals for addressing PFAS are focusing on research, restriction, and remediation. The strategic roadmap includes actions across the different divisions of USEPA. More information about USEPA's actions to address PFAS under this roadmap is available on their website (https://www.epa.gov/pfas), and in a November 2022 progress report (USEPA 2022).

8.2.2.4 Safe Drinking Water Act (SDWA)

The SDWA is the federal law that protects public drinking water supplies throughout the nation (USEPA 1974). Under the SDWA, the USEPA has authority to set enforceable National Primary Drinking Water Regulations, such as MCLs, for specific chemicals and to require testing of public water supplies. The SDWA applies to all public water systems (PWSs) in the United

States but does not apply to private domestic drinking water wells or to water not being used for drinking.

In June 2022, USEPA issued interim health advisories for PFOA and PFOS in drinking water (USEPA 2022). These replace the values USEPA issued in 2016 (USEPA 2016, 2016), and are subject to change upon finalization of a National Primary Drinking Water Regulation (NPDWR) that proposes maximum contaminant level (MCL) and maximum contaminant level goal (MCLG) values (USEPA 2023). In addition, in June 2022 USEPA issued final health advisories for GenX chemicals and PFBS in drinking water (USEPA 2022). See the Water and Soil Regulatory and Guidance Values Table Excel file for these values.

Much of the current occurrence data available regarding PFAS in public drinking water was generated by USEPA under the SDWA Unregulated Contaminant Monitoring Rule (UCMR) program (USEPA 2017). USEPA uses the UCMR to collect data for chemicals that are suspected to be present in drinking water but that do not have standards set under the SDWA. The third round of this monitoring effort, or UCMR3, included six PFAAs:

- perfluorooctanesulfonic acid (PFOS)
- perfluorooctanoic acid (PFOA)
- perfluorononanoic acid (PFNA)
- perfluorohexanesulfonic acid (PFHxS)
- perfluoroheptanoic acid (PFHpA)
- perfluorobutanesulfonic acid (PFBS).

Samples were collected during a consecutive 12-month monitoring period between 2013 and 2015 from large PWSs serving more than 10,000 people, and a limited number of smaller systems determined by USEPA to be nationally representative. Based on USEPA's UCMR3 reported limits of between 10 and 90 ng/L, depending on the specific PFAAs, at least one of the six PFAAs listed above was detected in 194 out of 4,920 PWSs tested (~4%), which serve about 16.5 million people in 36 states and territories (Hu et al. 2016).

The USEPA and some states use occurrence data produced by the UCMR program, not only for PFOA and PFOS, but also for other PFAS as well (Table 8-1 and Table 17-3), to help determine which substances to consider for future regulatory action. All of the data from the UCMR program are published in the National Contaminant Occurrence Database (NCOD) and available for download from USEPA's website (USEPA 2017).

Table 8-1. UCMR3 occurrence data for PFOA and PFOS

Chemical	**Analytical reporting limit (ppt)**	**Number of PWSs**[1]	**PWS (%)**[1]
PFOS	40	46	0.9
PFOA	20	13	0.3
∑ PFOA + PFOS		63	1.3
[1] Number and percent of public water systems (PWS) that exceeded the 2016 health advisory by chemical.			

The Fifth Unregulated Contaminant Monitoring Rule (UCMR 5) was published in December 2021. UCMR5 requires sample collection for 30 chemical contaminants between 2023 and 2025. This includes a list of 29 PFAS with minimum reporting limits ranging from 2 to 20 ppt (USEPA 2021). Individual PWS data will be reported online starting in 2023 (USEPA 2023). UCMR5 will include all US public water systems serving 3,300 or more people, which is a change from previous UCMRs that included systems serving 10,000 or more people.

The USEPA has not yet established final regulations for any PFAS under the SDWA. However, USEPA recently released a proposed rule that includes National Primary Drinking Water Regulations (NPDWRs) for six PFAS for public review and comment (USEPA 2023). In this draft rulemaking, USEPA has classified PFOA and PFOS as likely human carcinogens and proposes health-based MCLGs for PFOA and PFOS of zero, consistent with USEPA's approach for likely human carcinogens in general. The proposed and individual MCLs for PFOA and PFOS are at 4 ng/L, which is the analytical minimum reporting level and practical quantitation level. This draft rulemaking also proposes MCLGs and MCLs for the mixtures of PFHxS, Gen-X, PFNA, and PFBS at a total hazard index of 1 (unitless). USEPA expects to finalize this rulemaking in 2023. All six of these PFAS for which standards are being proposed are included in the UCMR5 analyte list.

For PFAS and other unregulated drinking water contaminants with limited occurrence data, the USEPA begins the process of making regulatory decisions under the SDWA by evaluating the nationwide extent of drinking water contamination and potential health effects that may result from exposure to contaminants via drinking water. This evaluation begins with considering contaminants for inclusion on the Contaminant Candidate List (CCL), which is a list of contaminants that are currently not subject to any proposed or promulgated national primary drinking water regulations but are known or anticipated to occur in public water systems. USEPA uses the CCL to identify priority contaminants for regulatory decision-making and information collection, including occurrence data collection under UCMR. On November 14, 2022, USEPA published the final CCL5, which includes PFAS as a chemical class (USEPA 2022).

In addition, when the USEPA determines there may be an "imminent and substantial endangerment" from a contaminant that is present in or likely to enter a PWS, under Section 1431 of the SDWA, it may issue emergency administrative orders (EAOs) to take any action necessary to protect human health if state and local authorities have not acted (42 U.S.C. §300i). USEPA has issued several such EAOs to protect public and private water supply wells contaminated with PFOA or PFOS (USEPA 2009, 2014, 2015, 2022).

8.2.2.5 Toxic Substances Control Act (TSCA)

TSCA authorizes the USEPA to require reporting, record keeping, testing, and restrictions of chemicals and chemical mixtures that may pose a risk to human health or the environment. Section 5 of TSCA authorizes the USEPA to issue Significant New Use Rules (SNURs) to limit the use of a chemical when it is newly identified, or when a significant new use of an existing chemical is identified, before it is allowed into the marketplace (USEPA 2017). From 2002 to 2013, USEPA issued four final SNURs covering 271 PFAS, including PFOS and PFOA. The first three SNURs covered PFAS included in the 3M Corporation's voluntary phaseout of PFOS. The 2013 SNUR required notification to USEPA prior to manufacture or import of seven PFAS that had been reviewed by USEPA under the TSCA New Chemicals Program but had yet to be commercially manufactured or imported into the United States. This SNUR also included long-chain perfluoroalkyl carboxylic acids (PFCAs) and their salts and precursors that were used in carpets or to treat carpets (USEPA 2015). Collectively, these SNURs placed notification requirements on the manufacture (including import) of specific PFAS for new use. The SNURs allowed for continued, low-volume use of some PFAS in photographic/imaging, semiconductor, etching, metal plating, and aviation industries (USEPA 2017). In January 2015, USEPA proposed another SNUR to require notification to USEPA before any future manufacture (including import) of PFOA and PFOA-related chemicals, including as part of articles, and processing of these chemicals. As a result of changes made to section 5(a) of TSCA when TSCA was amended in June 2016, USEPA undertook developing a supplemental SNUR for the import of certain long-chain PFCA and PFSAs as part of categories of certain articles (USEPA 2018).

As required by the NDAA, the USEPA finalized the supplemental SNUR in June 2020 and published the final notice in the Federal Register in July 2020 (https://www.govinfo.gov/content/pkg/FR-2020-07-27/pdf/2020-13738.pdf). The 2020 SNUR designates as a significant new use the manufacture, import, or processing of a specific subset of long-chain perfluoroalkyl carboxylate (LCPFAC) substances for any use that was not ongoing as of December 15, 2015, and for all other LCPFAC chemical substances for which there were no ongoing uses as of January 21, 2015. The SNUR also prohibits the import of certain LCPFAC as part of a surface coating on articles, and the import of carpet containing perfluoroalkyl sulfonate chemical substances, without USEPA review.

Finally, USEPA recently proposed a new SNUR for those PFAS that have not been manufactured (including imported) or processed for many years and are consequently designated as inactive on the TSCA Chemical Substance Inventory (USEPA 2023). Persons or companies subject to the SNUR would be required to notify USEPA at least 90 days before commencing any manufacture (including import) or processing of the chemical substance for a significant new use.

The USEPA continues to review new PFAS through USEPA's New Chemicals Program before approving commercialization. In October 2021, USEPA published the National PFAS Testing Strategy to "help EPA identify and select PFAS for which the Agency will require testing using TSCA authorities" (USEPA 2021). In 2023, USEPA released a new framework for addressing new PFAS and new uses of PFAS which is intended to require more extensive toxicity and fate data for PFAS with potential exposures or releases (USEPA 2023).

8.2.2.6 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)—"Superfund"

PFAS, including PFOA and PFOS, are not currently listed as CERCLA hazardous substances but may be addressed as CERCLA pollutants or contaminants, for example, as defined by section 101 (33) of CERCLA (40 CFR 300.5). USEPA published a proposal in September 2022 to designate PFOA and PFOS as hazardous substances (USEPA 2022). As listed above in Section 8.2.2.2, under its PFAS Action Plan (USEPA 2019), USEPA is evaluating listing PFOA and PFOS as hazardous substances. The action plan also includes a priority action to develop interim cleanup recommendations for groundwater contaminated with PFOA and PFOS. The USEPA released a draft recommendation for public comment in spring 2019, which includes using a screening level of 40 ppt for each (individually) of PFOA and PFOS (hazard index of 0.1), and using 70 ppt combined as a preliminary remediation goal. CERCLA investigations are beginning to include PFAS when supported by the CSMs (for example, (USEPA 2017). PFAS are often included in a remediation site's 5-year review, when supported by site-specific information.

CERCLA Protection of Human Health. CERCLA requires, among other things, that Superfund response actions ensure protectiveness of human health and the environment, and compliance with laws and regulations that constitute "applicable or relevant and appropriate requirements" (ARARs); the statute also provides possible ARAR waivers in limited circumstances. The lead agency (as defined in 40 CFR 300.5) identifies potential ARARs and to-be-considered values (TBCs), based in part on the timely identification of potential ARARs by states. Risk-based cleanup goals may be calculated and used to determine cleanup levels when chemical-specific ARARs are not available or are determined not to be sufficiently protective (USEPA 1997). The ARAR process can be complex and can result in impacts on scope, budget, and public acceptance components of a project (USEPA 2019).

The Water and Soil Regulatory and Guidance Values Table Excel file includes information from state, federal, and some international agencies. These values are not necessarily automatically recognized as ARARs and must be evaluated by the lead agency to determine their ARAR status. In the Superfund program, USEPA regions evaluate potential ARARs, including state standards, on a site-specific basis to determine whether a specific standard or requirement is an ARAR for response decision and implementation purposes. Determining if a state requirement is promulgated, substantive, and enforceable are some of the factors in evaluating whether a specific standard may constitute an ARAR or TBC (40 CFR 300.5 2001; 40 CFR 300.400 2019, (g); USEPA 1988, 1991).

As mentioned above, risk-based cleanup goals may be calculated when chemical-specific ARARs are not available or are determined not to be protective (USEPA 1997). The USEPA's Regional Screening Levels (RSLs) Generic Tables (USEPA 2023) and the RSL online calculator (USEPA 2017) are used by risk assessors to identify screening levels and preliminary remedial goals for contaminants of potential concern at a site. These goals are typically based on toxicity values that have been selected in accordance with the USEPA's published hierarchy (USEPA 2003). In May 2022, USEPA added five PFAS (PFOA, PFOS, PFNA, PFHxS, and GenX) to the RSL table (USEPA 2023). PFBS had previously been listed in the RSL generic tables. For these six PFAS, the generic tables provide noncancer reference doses (RfDs), screening levels for soil and tap water, and soil screening levels for the protection of groundwater. USEPA issued a final toxicity value for PFBS in April 2021 (USEPA 2021). In October 2021, USEPA issued a final toxicity assessment for GenX chemicals (USEPA 2021). The online RSL calculator currently supports site-specific calculations for the same six PFAS. The USEPA also provides tables and a calculator for removal management levels (RMLs). In general, RMLs are not final cleanup levels, but can provide a reference when considering the need for a removal action (for example, drinking water treatment or replacement) (USEPA 2016).

Because RSLs and RMLs are periodically updated, they should be reviewed for revisions and additions before using them. RSLs and RMLs are not ARARs, but they may be evaluated as TBCs. The USEPA has emphasized that RSLs and RMLs are not cleanup standards (USEPA 2023) and suggests that final remedial goals be informed by a baseline risk assessment so that site-specific information can be incorporated. Section 9 provides more information on site-specific risk assessment for PFAS.

CERCLA Protection of the Environment. CERCLA requires that remedies also be protective of the environment. Risk-based cleanup goals that are protective of the environment are site-specific and depend in part on the identification of the ecological receptors to be protected. Another example of a risk-based cleanup goal is a cleanup standard for a chemical in soil that is protective of groundwater quality and is developed on a site-specific basis. Given the challenge associated with deriving accurate physical and chemical properties for PFAS (Sections 4.1and 5.1), site-specific values will need to be derived.

8.2.2.7 Resource Conservation and Recovery Act (RCRA)

RCRA provides USEPA with the authority to regulate hazardous waste management, nonhazardous solid waste facilities and practices, and underground storage tanks holding petroleum or certain hazardous substances. No PFAS have been formally listed as RCRA hazardous waste for regulation under this program. However, there are at least a couple of examples where action on PFAS was taken under the auspices of RCRA. For example, in 2004 USEPA pursued violations of RCRA and TSCA at an E.I. DuPont de Nemours and Company (DuPont) facility in West Virginia due to environmental release of the hazardous constituent PFOA (USEPA 2015). In the case of DuPont, the facility already had a RCRA permit for hazardous waste disposal and was under a Corrective Action Permit. Some states, Texas, for example, are regulating certain PFAS under their RCRA permits and requiring investigation and cleanup.

In February 2017, a U.S. District Court denied motions to dismiss RCRA "imminent and substantial endangerment" claims relating to PFAS (*Tennessee Riverkeeper, Inc. v. 3M Co.*, No. 5:16-cv-01029-AKK, 2017 WL 784991 (N.D. Ala. Feb. 10, 2017)). This case involved the alleged continuing contamination of the Tennessee River and associated public drinking water supplies with PFAS that the plaintiff claims originated from a local manufacturing facility and two local landfills. There were several arguments that the claims should be dismissed. One argument by the landfill owners was that the claims were an attack on existing, valid permits that included a solid waste permit authorizing disposal in the landfill of PFAS-bearing materials. The court denied the motion to dismiss, stating that the permits only authorize disposal of nonhazardous waste, and there is a dispute over whether the PFAS-containing material is a hazardous waste. Additionally, there are a continually growing number of citizen lawsuits filed under RCRA in state courts throughout the United States. Thus, the applicability of RCRA regulations and statutes to PFAS does not appear to be settled and can be complicated.

On June 23, 2021, New Mexico Governor Michelle Lujan Grisham petitioned USEPA Administrator Michael Regan to designate PFAS as "hazardous waste" under the Resource Conservation and Recovery Act, citing imminent and substantial endangerment. On October 26, 2021, EPA administrator Regan responded to the governor's petition (USEPA 2021). In this response it was announced that USEPA will be initiating the process to add four PFAS (PFOA, PFOS, PFBS, and GenX) as RCRA Hazardous Constituents. In addition, there will be a rulemaking effort to clarify that RCRA has the authority to require the cleanup of solid wastes that meet the statutory definition of hazardous waste. This will mean that "emerging contaminants such as PFAS can be cleaned up through the RCRA corrective action process." (USEPA 2021).

8.2.2.8 Clean Air Act (CAA)

Under the CAA, USEPA is required to regulate emissions of hazardous air pollutants from industrial facilities. USEPA may develop standards for controlling certain hazardous air emissions from sources in a specific industry group. Within 8 years of establishing emission standards, USEPA must determine whether the standards are sufficiently protective of human health and protect against adverse environmental effects. This determination also considers improvements in air pollution controls and evaluates effective and feasible alternatives. There are no air emission standards for PFAS at this time. There is no indication how far along USEPA is in this process for regulating PFAS under the CAA.

8.2.2.9 Clean Water Act (CWA)

Since 1972, the CWA has given the USEPA authority to control water pollution by regulating discharges into the nation's surface water by setting wastewater standards for industry. There are no nationally recommended water quality criteria for any PFAS at this time. However, USEPA published draft aquatic life criteria for PFOA and PFOS in summer 2022 (USEPA 2022, 2022). USEPA released the Final 2016 Effluent Guidelines Program Plan in May 2018, which listed PFAS as a topic for future investigation (USEPA 2018). More recently, USEPA finalized Effluent Guidelines Plan 15 in January 2023 (USEPA 2023) (see Section 16.6).

In December 2022, USEPA released a memorandum relating to NPDES permitting for PFAS discharges which supersedes the April 2022 USEPA memo (USEPA 2022, 2022). More information about these USEPA documents can be found in Section 16.1. The regulation of PFAS in discharge effluents by states is discussed below in Section 8.2.3, and in Section 16.6.

8.2.2.10 Toxics Release Inventory (TRI) Program

The Toxics Release Inventory (TRI) program requires the annual reporting of environmental releases of approximately 800 chemicals which the USEPA has concluded cause:

- Cancer or other chronic human health effects
- Significant adverse acute human health effects
- Significant adverse environmental effects

For chemicals regulated under the TRI, facilities that manufacture, process or use these chemicals in amounts above established levels must submit annual reporting forms for each chemical.

As stipulated by the NDAA, the USEPA finalized a rule requiring 180 PFAS be added to the list of chemicals that must be reported under the TRI program for Reporting Year 2022 (USEPA 2023). An additional nine PFAS were added to the list for Reporting Year 2023 (USEPA 2023). The PFAS subject to TRI reporting requirements under the original NDAA included all

PFAS listed as an active chemical substances under TSCA's Section 8(b)(1) inventory. Each of these PFAS will have a 100-pound reporting threshold. In the 2022 changes to reporting requirements (USEPA 2022), these PFAS were added to the List of Lower Thresholds for Chemicals of Special Concern (chemicals of special concern), which eliminates the use of the *de minimis* exemption, which is expected to increase the reporting of PFAS found in mixtures or products in low concentrations (USEPA 2023). Reporting for each calendar year is due in July of the following calendar year; these data–as with all TRI data–will be publicly-available approximately 1 year after they were reported (USEPA 2020).

8.2.2.11 U.S. Food and Drug Administration (FDA)

One of the responsibilities of the FDA is regulation of "food contact substances" (FCSs), chemicals added to or components of "food contact materials" (FCMs), such as food wrappers and packaging. The FDA currently regulates certain PFAS used as grease-proofing agents for food packaging via a Food Contact Notification Program within the Center for Food Safety and Applied Nutrition's Office of Food Additive Safety. The PFAS used in FCMs and their known degradants and impurities have all undergone review for human health and environmental safety concerns through the food contact notification process and food additive petition process, which requires submission of chemical, toxicological, and environmental information on the FCS itself and on any potential impurities. Perfluorinated ion exchange membranes are also regulated under these processes.

In 2016 the FDA banned three perfluoroalkyl ethyl compounds from use in food packaging material (81 FRN 5, Jan. 4, 2016, Indirect Food Additives: Paper and Paperboard Components): diethanolamine salts of mono- and bis (1 H, 1H, 2H, 2H perfluoroalkyl) phosphates with even-numbered alkyl groups in the range of C8–C18; pentanoic acid, 4,4-bis [(*gamma–omega*-perfluoro-C8-20-alkyl)thio]; and perfluoroalkyl substituted phosphate ester acids, ammonium salts formed by the reaction of 2,2-bis[([gamma],[omega]-perfluoro C4–C20 alkylthio) methyl]-1,3-propanediol, polyphosphoric acid, and ammonium hydroxide.

In July 2020, the FDA announced that three manufacturers had agreed to a voluntary phase out of FCS that contain 6:2 fluorotelomer alcohol (6:2 FTOH). A fourth manufacturer had previously stopped sales of 6:2-FTOH-containing products in the US. The phase-out began in January 2021; the FDA predicted that it may take up to 18 months after that time to exhaust existing supplies of food contact papers that contain 6:2 FTOH (USFDA 2020).

As of February 2022, there were some FCS with PFAS listed on FDA's inventory of effective FCS notifications. The FDA (2023) inventory of FCS notifications is an online database. PFAS that are authorized for use in contact with food generally fall into four application categories:

- Nonstick cookware: PFAS may be used as a coating to make cookware non-stick.
- Gaskets, O-rings, and other parts used in food-processing equipment: PFAS may be used as a resin in forming certain parts used in food-processing equipment that require chemical and physical durability.
- Processing aids: PFAS may be used as processing aids for manufacturing other food contact polymers to reduce build-up on manufacturing equipment.
- Paper/paperboard food packaging: PFAS may be used as grease-proofing agents in fast-food wrappers, microwave popcorn bags, take-out paperboard containers, and pet food bags to prevent oil and grease from foods from leaking through the packaging (FDA 2019). However, the side-chain PFAS polymers used in grease-proofing are the subject of a voluntary phaseout agreement.

8.2.2.12 Other Federal Agency Actions

Other U.S. federal agencies and programs are actively involved in PFAS-related matters; however, their work largely focuses on data generation and analysis to help inform regulations/restrictions/regulatory action. These federal programs often provide valuable information, guidance, and resources for state regulatory and public health agencies. For example, the U.S. Centers for Disease Control and Prevention (CDC) National Health and Nutrition Examination Survey (NHANES) program provides valuable information about human exposure to chemicals (CDC 2023). Since 1999, the NHANES program has been providing an assessment of the exposure of the U.S. population to a small subgroup of PFAS. This information (PFAS concentrations in blood, serum, urine samples) is useful to scientists and regulatory agencies to understand "background" (that is, likely nonsite-related) human exposure levels and trends over time. In 2013-2014 CDC expanded their NHANES analysis to include evaluation of PFAS in serum and urine (Kato et al. 2018).

Under the Superfund Amendments and Reauthorization Act of 1986 (SARA) [42 U.S.C. 9601 *et seq.*] amendment to CERCLA (or Superfund) [42 U.S.C. 9601 *et seq.*], the U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry (ATSDR) was established to assess the potential public health risk from exposure to hazardous substances commonly found at National Priorities List facilities. CERCLA provides ATSDR with the authority to develop toxicological profiles that describe the health effects of these hazardous substances and to support site-specific response actions with health consultations and/or exposure investigations. A description of ATSDR's actions regarding PFAS is on their web page (ATSDR 2018). In May 2021, ATSDR released a final *Toxicological Profile for Perfluoroalkyls* (ATSDR 2021). In this revision, the agency discussed potential human health risks related to 14 specific PFAS and derived "provisional intermediate Minimal Risk Levels" (MRLs) for PFOA, PFNA, PFOS, and PFHxS.

ATSDR (2023) has posted an online calculator that the general public can use to estimate the increase in their blood serum levels from exposure to PFOA, PFOS, PFNA, or PFHxS in drinking water.

The U.S. Geological Survey (USGS) has had an emerging contaminants program for over a decade within which they measure emerging contaminants, including PFAAs, in various environmental media and ecological receptors. The objective of their work is to characterize environmental occurrence, sources, and source pathways that may contribute to environmental exposure. This has been a useful source of information for scientists and regulatory agencies on occurrence, fate, and transport of PFAS. Information on the USGS program can be found on their web page (USGS 2017).

The U.S. Department of Defense SERDP and ESTCP are jointly managed with USEPA and the U.S. Department of Energy to develop the latest science and technology to improve DOD's environmental footprint and mission capabilities. Beginning in fiscal year 2011, SERDP and ESTCP have funded a significant number of projects related to developing a better understanding of PFAS occurrence, fate and transport, ecotoxicity, and remediation treatments, as well as investigating the next generation of fluorine-free firefighting foams. More information on SERDP and ESTCP funding projects and statements of need can be found on their website (SERDP-ESTCP 2019).

8.2.3 State PFAS Regulations and Guidance

State regulatory agencies often have the delegated authority to regulate and enforce environmental and public health requirements, although the states and US territories have different priorities, resources, and processes. Many states have been actively involved with addressing PFAS contamination across multiple regulatory programs. Examples of key state programs for water, soil, remediation, hazardous substances, and consumer products are described below, and information about regulatory, advisory, and guidance values is discussed in Section 8.3. The information below is meant to provide examples only; the Water and Soil Regulatory and Guidance Values Table Excel file and the Air Criteria Table Excel file should be consulted for more current and detailed information.

The Association of State and Territorial Solid Waste Management Officials (ASTSWMO) has a PFAS resources website that includes links to PFAS information for states and territories (https://pfas.astswmo.org). The Environmental Council of the States (ECOS) published their updated white paper, Processes and Considerations for Setting State PFAS Standards, in March 2023 (ECOS 2023).

ITRC has developed the PFAS Regulatory Programs Summary Excel file that summarizes the regulations and programs in each state that target PFAS. The focus of the table is on PFAS regulations that have been enacted by any of the states or territories of the United States. The table also includes state programs that may not be mandated by a specific regulation, but which state agencies are pursuing on a discretionary basis. This table does not include any numeric criteria, but instead includes a description of the type of regulation or program, and a link to the applicable website. For specific regulatory values, the Water and Soil Regulatory and Guidance Values Table Excel file and the Air Criteria Table Excel file should be consulted.

The following subsections describe several different categories of state-adopted laws and regulations along with a brief explanation of each; please refer to the PFAS Regulatory Programs Summary Excel file for the most up-to-date information. Note that due to the state legislative review and finalization process, only bills that have been finalized into law are included in the PFAS Regulatory Programs Summary Excel file.

8.2.3.1 Product Labeling and Consumer Protection Laws

Several states have programs regulating PFAS in consumer products, including product labeling. Some of these regulations include PFAS in food packaging, children's products, firefighting gear, and other products. More specific information is available in the PFAS Regulatory Programs Summary Excel file with details available at the links provided.

8.2.3.2 Designation of Hazardous Waste or Hazardous Substance

Regulations that target select PFAS as hazardous wastes or hazardous substances have not been promulgated in most states. Formal PFAS regulations as hazardous substances have been promulgated in a number of states, and are under development in several other states. Please refer to the PFAS Regulatory Programs Summary Excel file for detailed information.

8.2.3.3 Drinking Water, Groundwater, Soil, and Remediation Programs

Several states have developed standards and guidance values for PFAS in drinking water, groundwater, and soil (see the Water and Soil Regulatory and Guidance Values Table Excel file). Some states adopted (by default) the USEPA LHAs published in either 2016 or 2022, while others adopted values developed via a risk assessment process, regulatory process, or legislative action. Some others use the LHA concentrations as advisory, nonregulated levels to guide the interpretation of PFAS detections. The May 2022 RSL table lists screening values for soil and tap water for six PFAS. Section 9 provides more information on site-specific risk assessment for PFAS.

In addition to the process using the USEPA RSL table mentioned above, some states have developed screening levels for various PFAS in soils assuming direct contact and/or ingestion. See the Water and Soil Regulatory and Guidance Values Table Excel file and USEPA (2021) Certain states have also developed values for the protection of groundwater (see the Water and Soil Regulatory and Guidance Values Table Excel file).

Some states have "antidegradation" policies aimed at protecting the quality of groundwater and high quality (or Tier 2) surface waters. Those polices can be used in decisions on cleanup and discharge under permits. Please see the PFAS Regulatory Programs Summary Excel file as well as the Water and Soil Regulatory and Guidance Values Table Excel file for more information.

8.2.3.4 Surface Water Discharge and Permitting

National Pollutant Discharge Elimination System (NPDES) permits use a standard process for developing effluent limits for pollutants. Effluent and receiving water limitations for PFAS would be established in the same manner as other pollutants. A number of states have established surface water quality standards for PFAS. More information on surface water effects can be found in Section 16.

8.2.3.5 Other State Regulations or Programs

Another concern for PFAS is in the application of biosolids from municipal wastewater treatment plants to land for disposal or reuse. A number of states are currently in the process of considering and/or developing such regulations (ECOS 2023). An example of this type of regulation may include a law to prohibit the land application of sludge as well as the sale and distribution of products containing sludge and septage. Other potential regulations may focus on reducing PFAS inputs into wastewater treatment plants while further assessing the impacts associated with land application of biosolids containing PFAS. See Section 3 for a more detailed discussion of PFAS in biosolids.

Some states have developed an ambient air limit for PFAS. See the PFAS Air Criteria Table and the PFAS Regulatory Programs Summary Excel file for more information.

Finally, some states have issued state regulations or programs related to AFFF. For example, some states have established AFFF take-back programs to reduce the potential discharge of PFAS associated with AFFF into the environment. Other states are in the process of developing an AFFF take-back program. See Section 3 for a more detailed discussion on AFFF and related regulations and guidance. A number of states have banned the manufacture, sale, and use of PFAS-containing AFFF in most applications (see PFAS Regulatory Programs Summary Excel file).

8.3 Differences in the Available Regulations, Advisories, and Guidance Regulatory

Human health protection is the primary focus of the PFAS regulations, guidance, and advisories developed to date. Internationally, including in the United States, the nonpolymer PFAS have been the regulatory focus. Several toxicity evaluations are available for certain PFAS. This is an area of active research and regulatory activity. Additional information is presented in Sections 7.1 and 17.2.

Human health–based guidance values and/or regulatory standards have thus far been derived for a number of PFAS, including PFAAs, polyfluoroalkyl precursors, and fluorinated ether carboxylates (FECA) by state and/or federal agencies in the United States. The health-based values for these nonpolymeric PFAS vary across programs, with differences due to the selection and interpretation of different key toxicity studies, use of human or animal data as the basis, use of a noncancer reference dose or a cancer slope factor, choice of uncertainty factors when a reference dose is used, and approaches used for animal-to-human extrapolation. The choice of exposure assumptions, including the life stage and the percentage of the reference dose assumed to come from non-drinking water sources, also differs. Most available guidance values and/or regulatory standards are for PFOA and PFOS, and the key differences in regulatory and guidance decisions within the United States for those chemicals can be seen in the ECOS white paper (ECOS 2023).

Table 8-2 provides the underlying definition and context for the various federal regulations, standards, and guidance values that may apply to PFAS in the United States.

Table 8-2. Definition of terms associated with drinking water and/or groundwater standards or guidance

Term	Acronym	Agency	Definition	Link
Minimum Risk Level	MRL	CDC ATSDR	An MRL is an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse noncancer health effects over a specified duration of exposure. MRLs are intended to serve as screening levels to identify contaminants and potential health effects that may be of concern. MRLs are not intended to define cleanup or action levels for ATSDR or other agencies. (ATSDR 2018) Importantly, the MRL is a daily dose, applicable for any oral exposure; it is not a threshold concentration in water or other environmental media.	https://www.atsdr.cdc.gov/mrls/index.asp

Term	Acronym	Agency	Definition	Link
Regional Screening Level	RSL	USEPA Regions	Default screening level tables including chemical-specific concentrations for individual contaminants in air, drinking water, and soil that may warrant further investigation or site cleanup. Generic screening levels (SLs) are based on default exposure parameters and factors that represent reasonable maximum exposure conditions for long-term/chronic exposures and are based on the methods outlined in EPA’s Risk Assessment Guidance for Superfund, Part B Manual (1991) and Soil Screening Guidance documents (1996 and 2002). It should be emphasized that SLs are not cleanup standards. (USEPA 2019)	https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide#intro

Term	Acronym	Agency	Definition	Link
Health Advisory	HA	USEPA Office of Water	Health advisories provide information on contaminants that can cause human health effects and are known or anticipated to occur in drinking water. EPA's HAs are nonenforceable and provide technical guidance to state agencies and other public health officials on health effects, analytical methodologies, and treatment technologies associated with drinking water contamination. (USEPA 2019)	https://www.epa.gov/dwstandardsregulations/drinking-water-contaminant-human-health-effects-information
Maximum Contaminant Level Goa	MCLG	USEPA Office of Water	The MCLG is the maximum level of a contaminant in drinking water at which no known or anticipated adverse effect on the health of persons would occur, allowing an adequate margin of safety. MCLGs are nonenforceable public health goals. MCLGs consider only public health and not the limits of detection and treatment technology effectiveness. (USEPA 2018).For contaminants classified as known or likely human carcinogens, it is USEPA policy to set the MCLG at zero (0). (USEPA 2023)	https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

Term	Acronym	Agency	Definition	Link
Maximum Contaminant Level	MCL	USEPA Office of Water	The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCL goals as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards. (USEPA 2018)	https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

8.3.1 Toxicity Values

As stated above, available PFAS regulations, guidance, and advisories are generally based on human health protection. However, the available values that are deemed protective of human health vary across international and U.S. jurisdictions. In general, there are similarities and differences in the understood toxicological effects, potencies, and modes of action for various PFAS, and there are differences in the interpretation of relevant toxicological data for individual PFAS.

Toxicological data from both animal and human epidemiology studies are used as the basis for U.S. state and federal PFAS human health toxicity factors and related standards or guidance. The European Food Safety Authority's tolerable weekly intake for the total of PFOA, PFOS, PFNA, and PFHxS is based on human data (EFSA 2020). More recently, California EPA and USEPA have developed draft reference doses for PFOA and PFOS (CA OEHHA 2023; USEPA 2023), as well as for PFHxS (USEPA 2023) and PFDA (USEPA 2023), and a draft cancer slope factor for PFOA (USEPA 2023; CA OEHHA 2023) based on human general population data that are far below current values based on animal data. See Section 7 for a review of the toxicology data for PFAS. Many scientific considerations and decision points are involved in developing human health toxicity factors (RfDs and cancer slope factors) from animal toxicology data or human epidemiology data. For PFOA and PFOS, different scientific and regulatory policy conclusions have been made for nearly every decision point by different agencies. Some of the key topics that account for toxicity value differences are discussed below. More specific information on these differences can be found in the Water and Soil Regulatory and Guidance Values Table Excel file; as well as the PFAS Regulatory Programs Summary Excel file and the ECOS white paper (ECOS 2023).

Although previous PFAS regulations, standards, and guidance have largely been based on potential noncancer effects, several recent draft or proposed values are based on cancer risk. RfDs have been used by most U.S. states to describe the estimate of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime (USEPA 2019).

The New Jersey Drinking Water Quality Institute (NJDWQI) and California Office of Environmental Health Hazard Assessment (OEHHA) also considered potential cancer endpoints for PFOA and PFOS. In its recent proposed PFAS MCL rule, USEPA (2023) classified both PFOA and PFOS as likely human carcinogens and developed cancer slope factors for both. NJDWQI (2023) concurred with USEPA (2023) that PFOA is a likely human carcinogen. However, at the time of New Jersey's recent analysis, the NJDWQI (2023) was unaware of the information identified by USEPA (2023) that is the basis for its conclusion that PFOS is also a likely human carcinogen. The methodology for deriving chemical-specific toxicity values is generally applicable to both cancer and noncancer endpoints where dose-response relationships and weight-of-evidence analyses of available data sets are evaluated, and is described in detail.

The first step in deriving a human health-based toxicity value (RfD or CSF) is the review of applicable data to identify potential human health hazards (toxicity endpoints) based on sensitive effects that are consistently seen across several studies, are deemed related to an adverse health outcome or its known precursor, and are relevant to humans based on mode of action considerations. Not all agencies have utilized the same candidate studies and health endpoints for PFOA and PFOS due to differences in selection criteria and differences in opinion on the relevancy to human health and on adversity of effects seen in recent studies.

The estimation of an RfD includes two additional components: the selection of the dose-response method and uncertainty factors. For dose-response evaluation, either the benchmark dose or the study NOAEL or LOAEL is utilized as the point of departure. Uncertainty factors used include the standard risk assessment extrapolations, and the choice of uncertainty factors also varies by agency.

8.3.2 Exposure Assumptions

General exposure factors that are used in derivation of PFAS regulations and guidance values are discussed below.

8.3.2.1 Body Weights, Drinking Water Ingestion, and Exposure Durations

Once a human health toxicity value is derived in units of ug/kg-day (or ng/kg-day or mg/kg-day), the toxicity value is combined with exposure parameters to result in the ultimate threshold concentration in drinking water (guidance or standard). The choice of exposure parameters used can be a flexible science- and/or policy-based decision based on default assumptions or chemical-specific data, or may be set based on regulatory framework. The exposure parameters used under the U.S. CERCLA program (for example, USEPA regional screening levels) include default exposure parameters and factors that represent conditions for long-term/chronic exposures, including an exposure frequency of 350 days per year, exposure duration of 6 years for a 15-kg child who drinks 0.78 L water per day, or 26 years for an 80-kg adult who drinks 2.5 L of water a day. In contrast to CERCLA, drinking water guidance values and standards (MCLs and MCLGs) developed by USEPA or states are generally based on lifetime exposure using default adult parameters, and they do not usually include a duration of exposure parameter. For PFOA and PFOS, USEPA and state agencies have not always relied upon these default exposure parameters. Some have decided to utilize exposure parameters that are specific for more sensitive subpopulations (infants, children, or lactating/pregnant women) and/or a toxicokinetic model that considers exposures to the developing fetus and the higher exposures to the breast-fed infant. For example, MDH developed a toxicokinetic model to estimate the total exposure to breast-fed and formula-fed infants (Goeden, Greene, and Jacobus 2019), and this model was used to derive standards in Minnesota, New Hampshire, and Michigan.

8.3.2.2 Relative Source Contribution

Humans can be exposed to nonpolymeric PFAS, including precursor chemicals, via multiple sources, including air, food, and consumer and industrial products. The relative source contribution (RSC) term is used in health-based guidance and standards developed by the USEPA under the federal SDWA and related state programs to account for potential non-drinking water exposures to chemicals. In general, the concept ensures that when a criterion based on an RfD for noncancer effects is established for a single exposure pathway, such as drinking water, potential exposures that occur from other pathways are accounted for so that total exposure does not exceed the RfD (USEPA 2000). The default RSC of 20% means that the drinking water pathway is assumed to contribute only 20% of the RfD, and all other exposure pathways contribute the remaining 80%. In practice, therefore, the drinking water concentration based on RfD and drinking water consumption assumptions is multiplied by the RSC (for example, 20%) to account for exposure via the other pathways.

The RSC term generally does not exist in CERCLA/RCRA-based remediation programs because baseline risk assessments specifically investigate and quantify risks associated with all potential site-specific exposure routes (not just drinking water), and then consider a receptor’s cumulative risk. Therefore, there is no downward adjustment to a residential groundwater (termed “tap water” by USEPA) drinking water screening level, for example, to account for potential other exposures—all site-specific exposures are quantified. See Section 9 for more information on site-specific risk assessments for PFAS.

Updated September 2023.

9 Site Risk Assessment

The PFAS Team developed a Risk Assessment and Regulations training video with content related to this section. The video provides information on the fundamentals of risk assessment and an overview of the challenges associated with conducting risk assessments for PFAS.

This section discusses the specific challenges associated with assessing and characterizing potential risks to human and ecological receptors exposed to PFAS in the environment. This includes challenges associated with quantifying the degree of exposure, assessing the hazard associated with PFAS, quantifying the dose-response relationship, and characterizing risks to support effective risk management decision-making. Generally, the challenges associated with performing a site risk assessment where the release of PFAS to the environment is suspected are not necessarily unique. Like any other chemical for which there is limited information, knowledge, or other technical complexity, working through the steps necessary to complete a risk assessment would be similar.

Section 15.3 provides a case study example illustrating how the New Jersey Department of Environmental Protection used risk assessment science to help support the development of fish consumption advisories for select water bodies in New Jersey. Section 17.3 provides additional information related to PFAS risk assessment, including (1) exposure pathways relevant for different exposure media, (2) considerations when calculating exposure point concentrations, and (3) selecting bioconcentration/bioaccumulation factors.

Section Number	Topic
9.1	Human Health Risk Assessment
9.2	Ecological Risk Assessment
9.3	Uncertainty

9.1 Human Health Risk Assessment

9.1.1 Toxicity Assessment

The toxicity assessment of a site risk assessment involves (1) hazard identification and (2) dose-response assessment. Hazard identification involves determining whether exposures to a chemical can cause an increased risk of an adverse human health effect; dose-response assessment involves quantifying the relationship between the degree of exposure to the chemical and the incidence or severity of the potential adverse effects. More background on each of these steps is detailed in other guidance (USEPA 1989; ITRC 2015) and is not repeated here.

This section discusses specific complications that may be encountered in completing the toxicity assessment for a site risk assessment involving PFAS.

9.1.1.1 Availability of Toxicity Values from a Variety of Sources

A toxicity value (for example, oral cancer slope factor (CSF), or reference dose (RfD)) is a numerical expression of the dose-response relationship for a given substance. It is used in combination with estimates of chemical exposure to calculate quantitative estimates of cancer risk or noncancer hazard (USEPA 1989). Several state, national, and international regulatory and advisory agencies have developed human toxicity values for various PFAS that could be potentially used in conducting risk assessments or in support of establishing policies for PFAS risk management. Given this variety of sources, specific complications can be encountered in determining which toxicity values to use in conducting a risk assessment:

- Selection of toxicity values for PFAS is dependent on which PFAS are present at a given site. PFAS identification and quantification may vary based on analytical method.
- Differences among toxicity values for PFAS could arise because agencies may rely on different toxicity value derivation methods; select critical studies by different criteria, including animal or human data; use different

uncertainty factors; and prioritize individual PFAS differently for toxicity value derivation. Table 9-1 provides an example for PFOA and PFOS, showing that USEPA used human data while ATSDR used animal data.

- Available toxicity values may change over time as the results of new studies become available. Newer toxicity values derived by regulatory agencies may be based on more recent and/or different information, methods, and studies than older values, as well as differences in scientific professional judgment and/or different statutory policy requirements. These differences are described in more detail in Section 8.3.
- States may choose to derive their own toxicity values rather than use those developed by the USEPA, and values developed by other countries may differ from USEPA's.
- Some states may perform route-to-route extrapolation (from oral toxicity values to inhalation toxicity values) for evaluation of the inhalation pathway. However, uncertainties should be noted if using route-to-route extrapolation.

Table 9-1. Example of variability in noncancer toxicity factors for PFOA and PFOS—USEPA (2023),2023 draft RfDs and ATSDR (2021) MRLs.

	Noncancer Toxicity Values for Human Health Risk Assessment (ng/kg body weight*day)			
Source	***PFOA***	**Basis**	***PFOS***	**Basis**
USEPA Office of Water (2023) **DRAFT** USEPA (2023) USEPA (2023) Reference Doses (RfDs)	0.03	Decreased antibody response to tetanus and diphtheria vaccinations in children, low birth weight, and increased total cholesterol	0.1	Low birth weight and increased total cholesterol in humans
ATSDR (2021) Minimal Risk Levels (MRLs)	3	Behavioral and skeletal effects in mice (following developmental exposure)	2	Delayed eye opening and decreased pup weight in rats

The most recent RfDs available should be used when preparing a human health risk assessment.

There are several options and procedures for selection of toxicity values, as has been described in ITRC guidance (ITRC 2015). For site risk assessments performed in the United States, USEPA, DOD, and other agencies have recommended a tiered hierarchy (Tier 1–Tier 3) of toxicity value sources to guide selection and use (USEPA 2003, 2013); (ECOS-DOD 2007). This recommendation has since been implemented in numerous USEPA OSWER (Currently known as Office of Land and Emergency Management) directives (USEPA 1993, 2003, 2022) that further establish a hierarchy and process for selecting toxicity criteria. For PFAS chemicals as of March 2023:

- Tier 1 values are peer-reviewed toxicity values published on the USEPA's Integrated Risk Information System (IRIS).
    - IRIS values are available for PFBA (USEPA 2022) and PFHxA (USEPA 2023)
    - Draft IRIS assessments and toxicity values are available for PFDA (USEPA 2023) and PFHxS (USEPA 2023), and an IRIS assessment and toxicity values for PFNA are under development. The status of the PFAS IRIS assessments can be found in the latest IRIS Program Outlook, available at https://www.epa.gov/iris/iris-program-outlook.
- Tier 2 toxicity values include Provisional Peer-Reviewed Toxicity Values (PPRTV).
    - PPRTV values are available for PFBS (USEPA 2021)
- Tier 3 toxicity values include those from additional USEPA and non-USEPA sources. They can include values that may or may not have been peer reviewed. As recommended by USEPA (2003), in using values from Tier 3 sources, it may be appropriate to prioritize those that are the *most current*, have a *transparent* basis, are *publicly available*, have been *peer reviewed*, and are acceptable to local jurisdictions. USEPA (2022) prioritized available Tier 3 sources of toxicity values in its regional screening level (RSL) guidance, with the current relevant sources for PFAS identified as:
    - ATSDR minimal risk levels (MRLs) (for example, the oral MRLs for PFNA and PFHxS (ATSDR 2021))

    - USEPA Office of Water health advisories or human health toxicity assessments (for example, the oral toxicity value presented in the drinking water health advisory for GenX [USEPA 2021; USEPA 2022])
    - California Environmental Protection Agency Office of Environmental Health Hazard Assessment (CA OEHHA 2023)
- Additional definitions and discussion of PFAS toxicity values that are available for use are provided in Section 7 and Section 17.2.

The USEPA will continue to develop toxicity values for PFAS. In addition, USEPA may continue reviewing available Tier 3 toxicity values and recommending values in RSL table updates. Individual risk assessors can also select Tier 3 values as appropriate (when no Tier 1 or 2 values are available).

9.1.1.2 Characterizing Cancer Risk for Exposure to PFAS

The draft USEPA documents that provide the toxicological basis for the proposed USEPA maximum contaminant level goals (MCLGs) for PFOA and PFOS conclude that both PFOA and PFOS are likely to be carcinogenic to humans (USEPA 2023, 2023, 2023). The draft USEPA MCLGs for PFOA and PFOS are zero, consistent with USEPA's general approach for MCLGs for known or likely human carcinogens. The International Agency for Research on Cancer (IARC 2016) classified PFOA as possibly carcinogenic to humans (Class 2B). IARC is currently re-evaluating the carcinogenic potential of PFOA and is evaluating the carcinogenic potential of PFOS (IARC 2023). A recent review by NJDWQI (2023) concurred with USEPA that PFOA is a likely human carcinogen; this review also concluded that PFOS has suggestive evidence but was not aware of some animal tumor data relevant to this evaluation that was considered by USEPA (2023) (see Section 17.2.5.3).

For GenX, USEPA concluded that there is suggestive evidence of carcinogenic potential in humans based upon liver, pancreatic, and testicular tumors observed in chronic rat studies, but also concluded that these data lacked a dose-response relationship and therefore did not support development of a CSF (USEPA 2022).

Although most risk-based values and screening levels developed by states have been primarily based on noncancer effects, USEPA and some select states (for example, New Jersey—NJDWQI 2017, 2018; California—OEHHA 2023) have derived oral CSFs for PFOA and PFOS. NJDWQI (2017) developed identical drinking water concentrations for PFOA using the RfD for noncancer effects and the CSF and the 1 in 1 million cancer risk level. For PFOS, NJDWQI (2018) concluded that, although the CSF was too uncertain for use as the quantitative basis to develop a drinking water level, the level based on noncancer effects did not pose an unacceptably high cancer risk. CalEPA's CA OEHHA (2019), however, issued notification levels for drinking water exposure, and developed draft public health goals (PHGs) for PFOA and PFOS that are driven by carcinogenicity (CA OEHHA 2023). The draft PHG for PFOA is based on kidney cancer in humans; the PHG for PFOS is based on liver and pancreatic tumors in rats (CA OEHHA 2023). As part of the basis for the proposed USEPA MCLs for PFOA and PFOS, USEPA (2023; 2023; 2023) developed a draft CSF for PFOA of 0.0293 $(ng/kg/day)^{-1}$ (i.e., 29,300 $[mg/kg/day]^{-1}$) based on kidney cancer in the human general population and a draft CSF for PFOS of 39.5 $(mg/kg/day)^{-1}$ based on liver tumors in rats. For site risk assessments, the derived CSFs developed by these agencies could be used.

Further discussion of the carcinogenicity of PFAS is presented in Section 17.2.4.2 (Carcinogenicity), Section 17.2.5.3 (Chronic Toxicity and Tumorigenicity), and Section 8.2.2.6 (CERCLA).

9.1.1.3 Lack of Toxicological Values for Many PFAS

There are several thousand PFAS that could have been, or may be, on the global market (OECD 2018), although the uses of all of these PFAS may not be known (KEMI 2015). More information about PFAS in use is included in Section 2. In general, PFAS are considered to be bioavailable (i.e., following exposure, they are absorbed and enter the systemic circulation). However, toxicity values have been developed for only a few PFAS for which sufficient information is available. Because of the lack of hazard and dose-response information for other PFAS and the extensive level of effort needed to develop toxicity values, there are no readily available toxicity values for the majority of PFAS.

This lack of information precludes the establishment of compound-specific risk-based concentrations that can be helpful for a variety of applications, including data screening (used to help guide site investigation) and site-cleanup decision-making. In the absence of toxicity values, regulatory agencies and the regulated community are left with uncertainty regarding the potential risks associated with human exposure to impacted environmental media at sites, difficulties with creation of technically defensible risk management programs, and inability of the regulated community to be responsive to concerns about environmental risk.

An approach often used in HHRA in the absence of compound-specific toxicity values is to use toxicity values developed for structurally or chemically similar surrogate compounds with similar biological activity. In the case of PFAS, this would be for PFAS from the same structural subgroup (for example, long-chain perfluorocarboxylic acids). The use of surrogates, however, introduces uncertainty, because surrogates may produce adverse health effects by mechanisms different from the compound of concern, the dose-response curve for a surrogate may be different, and the target organ or toxicity endpoint may be different from the compound of concern. In the absence of chemical-specific toxicity values, preparation of health risk assessments may be limited to qualitative methods and have a higher level of uncertainty in the human health risk assessment as a result.

Further information and guidance are needed to identify appropriate surrogates for PFAS that do not currently have available toxicity values. USEPA's PFAS Action Plan (USEPA 2019) noted that USEPA would be working on developing an approach to PFAS toxicity testing that could lead to a methodology for inferring the toxicology of a given PFAS based on the toxicology of a PFAS subset whose toxicology is known. This involves "applying computational and high throughput toxicology tools for PFAS toxicity testing on a larger scale to enable faster understanding of potential toxicity for the universe of thousands of PFAS, most of which have little or no published toxicity data" (USEPA 2022). A more thorough discussion of new assessment methods (NAMs) can be found in Section 17.2.7.

The USEPA has developed its National PFAS Testing Strategy in which PFAS manufacturers will be issued orders under Toxic Substances Control Act (TSCA) authorities to perform toxicity testing on compounds representative of certain PFAS classes (USEPA 2021). These classes are organized by similarities in structure, physical-chemical properties, and existing test data on compound toxicity. Thus, there is a plan to obtain toxicity information for each class via a representative compound that will potentially serve as a surrogate for the other compounds in the class.

9.1.2 Exposure Assessment

The exposure assessment of a site risk assessment involves characterizing the exposure setting, identifying relevant exposure pathways and scenarios, and quantifying the magnitude, frequency, and duration of potential human exposure to chemicals in environmental media. More background on the performance of exposure assessments is detailed in other guidance (USEPA 1989; ITRC 2015) and is not repeated here.

This section discusses specific complications that may be encountered in completing the exposure assessment for a site risk assessment involving PFAS. It should be recognized that the exposure assessment does not generally account for the presence of all PFAS at a site due to limitations in analytical methods. Therefore, there are uncertainties in the characterization of exposures (and associated risks) at PFAS sites that should be acknowledged in the uncertainty analysis section of the risk assessment.

PFAS may be present in biosolids at levels of potential concern. If biosolids contain PFAS and are applied to agricultural fields, the PFAS may contaminate crops and livestock. Blaine et al. (2013) evaluated the uptake of PFAAs contained in industrially impacted biosolids-amended soil and municipal biosolids-amended soil by various crops and confirmed "that the bioaccumulation of PFAAs from biosolids-amended soils depends strongly on PFAA concentrations, soil properties, the type of crop, and analyte." In addition, Lindstrom et al. (2011) evaluated the impacts of PFAS-contaminated biosolids from a local municipal wastewater treatment facility (that historically received waste from fluorochemical facilities) used as a soil amendment in local agricultural fields. Results showed relatively high transport from soils to surface water and groundwater in the vicinity of the agricultural fields. Based on these studies, two potential exposure pathways to PFAS in biosolids are drinking water ingestion and food ingestion. A discussion of the leaching potential from soil to groundwater for biosolids is provided in Section 6.2.3. As indicated in Section 6.2, a 2021 review of reported values for biosolids, compost, and related biowastes highlights the wide concentration range of reported PFAS (primarily PFAAs) and the relationship of biowaste source to resulting concentrations (Bolan et al. 2021).

Biosolids as a potential source of PFAS are mentioned in USEPA's (2021) PFAS Strategic Roadmap. USEPA is currently conducting a risk assessment for PFOA and PFOS in biosolids and expects to have the risk assessment finalized in 2024.

9.1.2.1 Determining Scenarios for Potential Human Exposure

A site-specific conceptual exposure model should be developed during the planning stage of the HHRA, confirmed by stakeholders, and updated as additional information and data are obtained, (see Section 3 of the RISK-3 guidance (ITRC 2015)). The specific exposure scenarios that are applicable to an HHRA for PFAS include those that could occur in media at the release area (the site) and in media at distant locations (with the extent depending on PFAS properties and the site setting). In general, an HHRA for PFAS may be complex in comparison to HHRAs for other types of chemicals due to the persistence of PFAS, the complexities associated with PFAS toxicity, and complexities associated with estimating future concentrations or modeling their fate and transport, and the need to include more media than is typical. Figures 9-1, 9-2 and 9-3 are provided below to illustrate conceptual site models (CSMs) for four sources (two sources are illustrated in Figure 9-3) of PFAS. Section 2.6 discusses potential environmental releases of PFAS. A detailed discussion of fate and transport processes for PFAS and environmental media that may be affected is presented in Section 5.

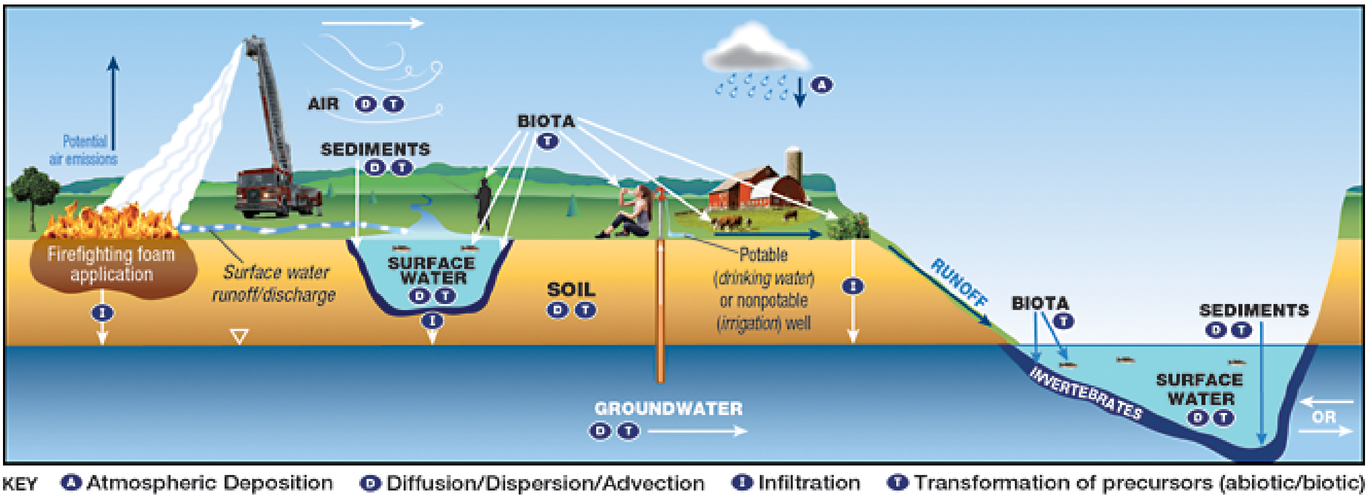


Figure 9-1. CSM for fire training area.

Source: Adapted from figure by L. Trozzolo, TRC. Used with permission.

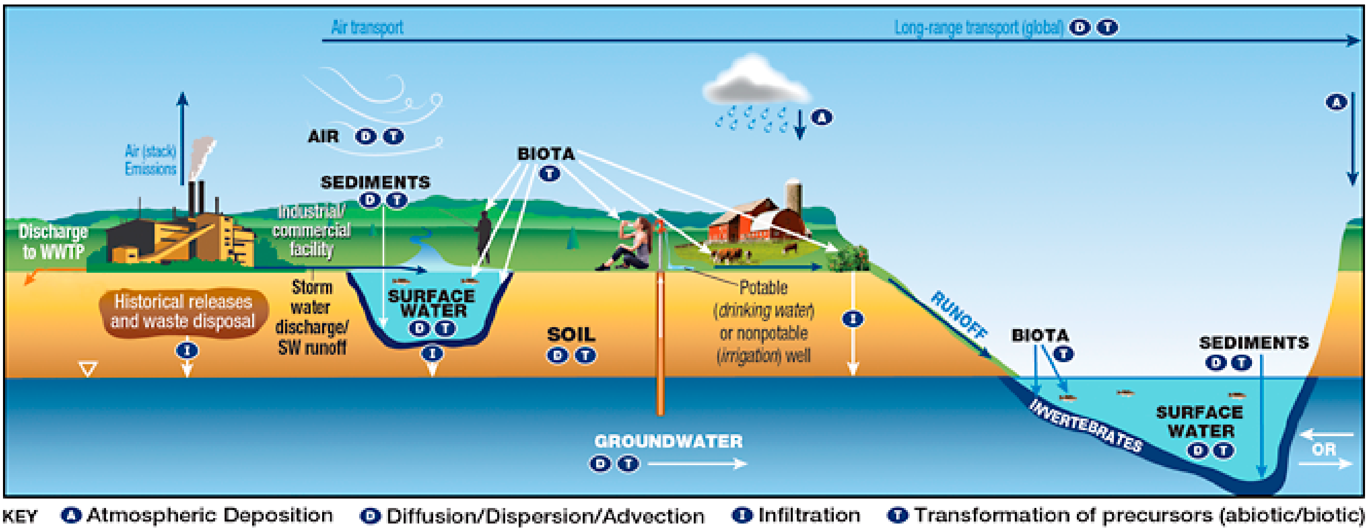
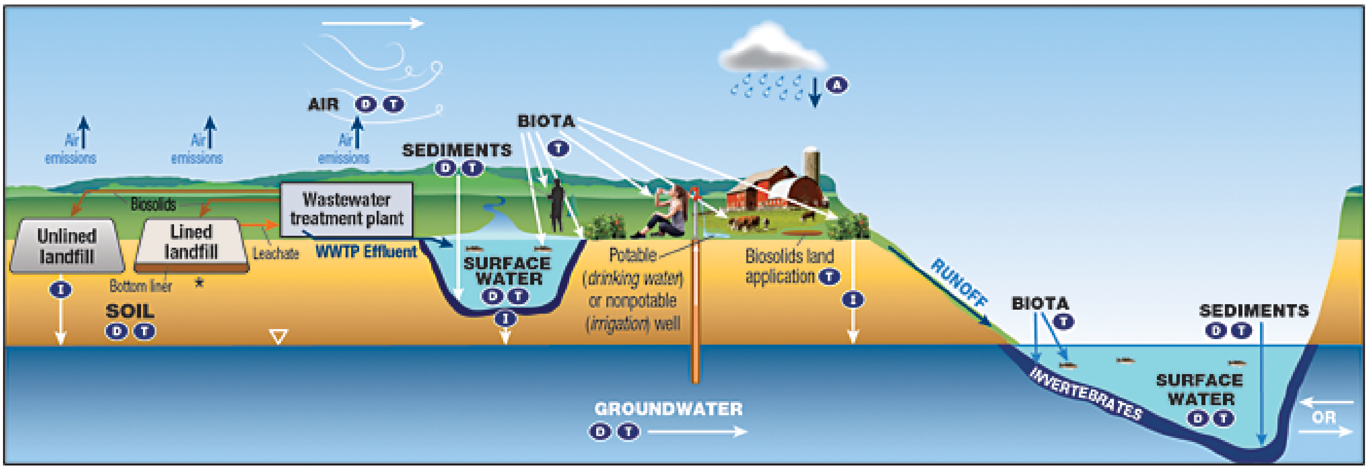


Figure 9-2. CSM for industrial sites.

Source: Adapted from figure by L. Trozzolo, TRC. Used with permission.



*Leachate release from lined landfills could occur in the event of a liner leak

KEY Ⓐ Atmospheric Deposition Ⓓ Diffusion/Dispersion/Advection Ⓘ Infiltration Ⓣ Transformation of precursors (abiotic/biotic)

Figure 9-3. CSM for landfills and WWTPs.

Source: Adapted from figure by L. Trozzolo, TRC. Used with permission.

Various exposure scenarios may be possible for a given site. Specific exposure scenarios that could be included in an HHRA are a site-specific decision.

The highest exposures to PFAS can occur during early life stages (Goeden, Greene, and Jacobus 2019). Exposures to infants from breast milk of exposed mothers (Figure 9-4) or formula prepared with contaminated water are higher (on a body weight basis) than in older age groups (Fromme et al. 2009; Mogensen et al. 2015; Verner et al. 2016, Verner et al. 2016; Post, Cohn, and Cooper 2012; Goeden, Greene, and Jacobus 2019). The higher exposures during pregnancy and to infants are of concern because fetuses and infants are potentially sensitive subpopulations for developmental effects of some PFAS, including PFOA and PFOS (USEPA 2023, USEPA 2023), as discussed in Section 7.1. Therefore, exposure scenarios that include fetuses, infants, children, adolescents, and women of childbearing years should be considered in HHRAs.

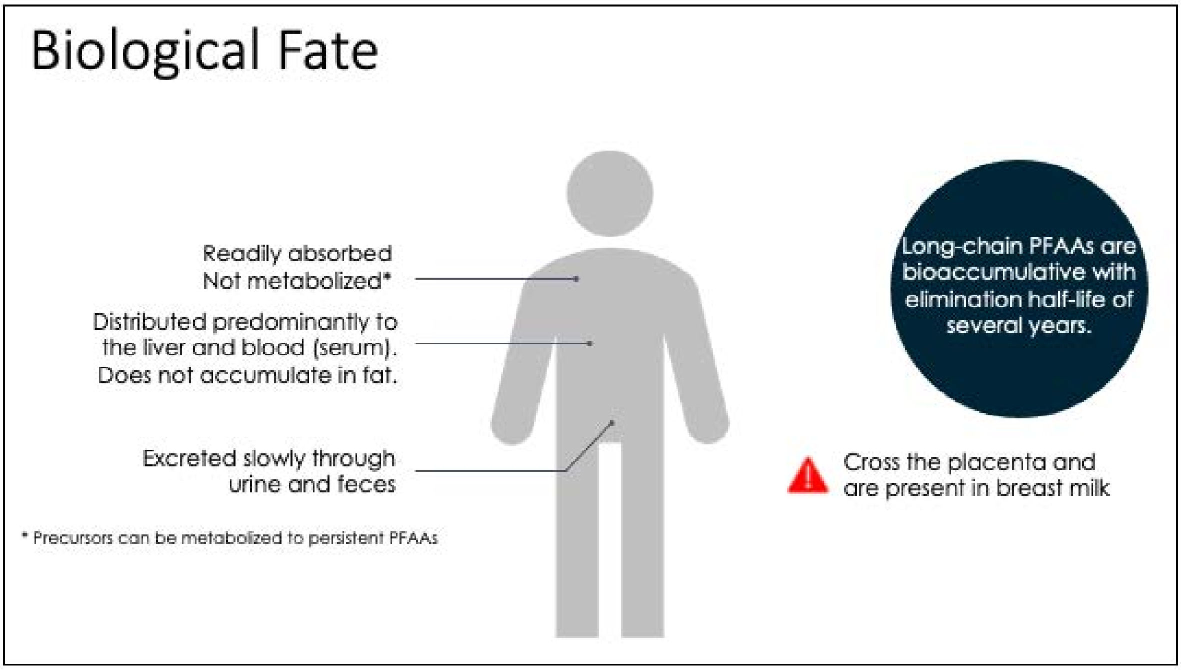
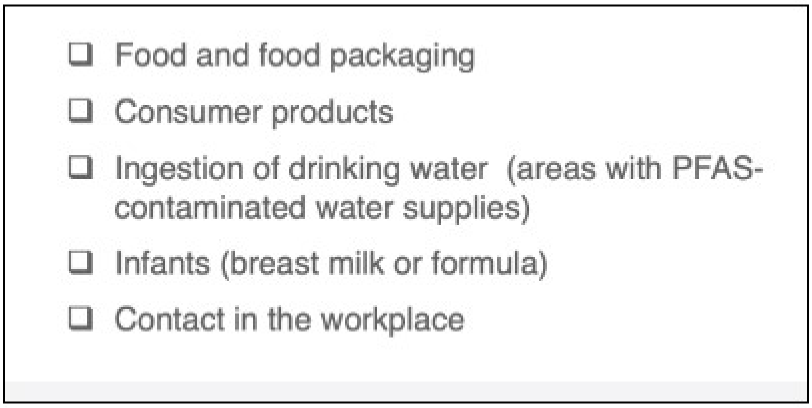


Figure 9-4. Biological fate of long-chain PFAAs.

Figure 9-5 illustrates the predominant exposure pathways. More detailed information about these exposure pathways, as well as other environmental medium-specific issues affecting potential human exposure scenarios, are provided in Section 17.3.1.



☐ Food and food packaging
☐ Consumer products
☐ Ingestion of drinking water (areas with PFAS-contaminated water supplies)
☐ Infants (breast milk or formula)
☐ Contact in the workplace

Figure 9-5. Predominant human exposure pathways.

9.1.2.2 Calculating Exposure Concentrations for PFAS via Fate and Transport Models

When using fate and transport models to calculate exposure point concentrations (EPCs) for PFAS, it is important to note that individual PFAS have different chemical properties that affect their fate in the environment (Section 5). Some PFAS are mobile, persistent, and bioaccumulative (in wildlife and humans), and others are not. Perfluoroalkyl acids (PFAAs) are persistent, and long-chain PFAAs bioaccumulate in humans (USEPA 2003; ATSDR 2020; NTP 2016; CONCAWE 2016). USEPA has compiled an online resource for PFAS information that includes guidance on environmental behavior and site characterization (USEPA 2017). The National Groundwater Association (NGWA) has also published a resource on PFAS that includes information about fate and transport (NGWA 2017). Section 5.2.3 provides a discussion of fate and transport modeling for PFAS, including numerous citations. Additional information is included in Section 17.3.2.

When using environmental fate and transport models for estimating EPCs in biota, modeling should be focused on the part of the organism that may be consumed either by humans or by ecological receptors, recognizing that patterns of consumption may be influenced by a number of socioeconomic and cultural factors. PFAS generally bind to proteins and accumulate in protein-rich tissues, including the blood, liver, and kidneys (ATSDR 2020). Plant uptake and bioaccumulation and partitioning within the plant appear to depend on PFAS chemical structure and the plant species (see Section 5.6). Section 17.3.3 includes information about selecting bioaccumulation and bioconcentration factor values.

Measured concentrations at exposure points may differ from modeled EPCs. This may be due to other sources of PFAS (for example, a nearby site that had a PFAS release to the ground and that subsequently leached to groundwater) also contributing to concentrations at the exposure point and the limitations of the models currently available.

In surface water bodies, PFAS concentrations in foam formed at the air-water interface from wind or wave action may be much higher than PFAS concentrations present in the water column (see Section 16.5). Therefore, in surface water bodies where foam is present, the need to evaluate exposures to foam should be considered when planning an HHRA. At sites where foam exposures are evaluated in the HHRA, EPCs should be established separately for foam and surface water so that potential risks to foam are not underestimated.

9.1.3 Risk Characterization

The risk characterization of a site risk assessment combines the results of the exposure assessment and the toxicity assessment to provide a quantitative estimate of risk (ITRC 2015). It also may include a qualitative narrative designed to provide decision makers with information regarding key assumptions, uncertainties, or other issues that would be important to understand when making risk management decisions. More background on the performance of risk characterizations is detailed in other guidance (USEPA 1989; ITRC 2015) and is not repeated here.

Because risk characterization involves combining the toxicity assessment and exposure assessment, the complexities discussed in Sections 9.1.1 and 9.1.2 manifest themselves in the risk characterization. There are, however, additional specific complications that may be encountered in completing the risk characterization for a site risk assessment involving PFAS. This section discusses those specific complexities.

9.1.3.1 Assessing the Cumulative Effects of Exposure to PFAS

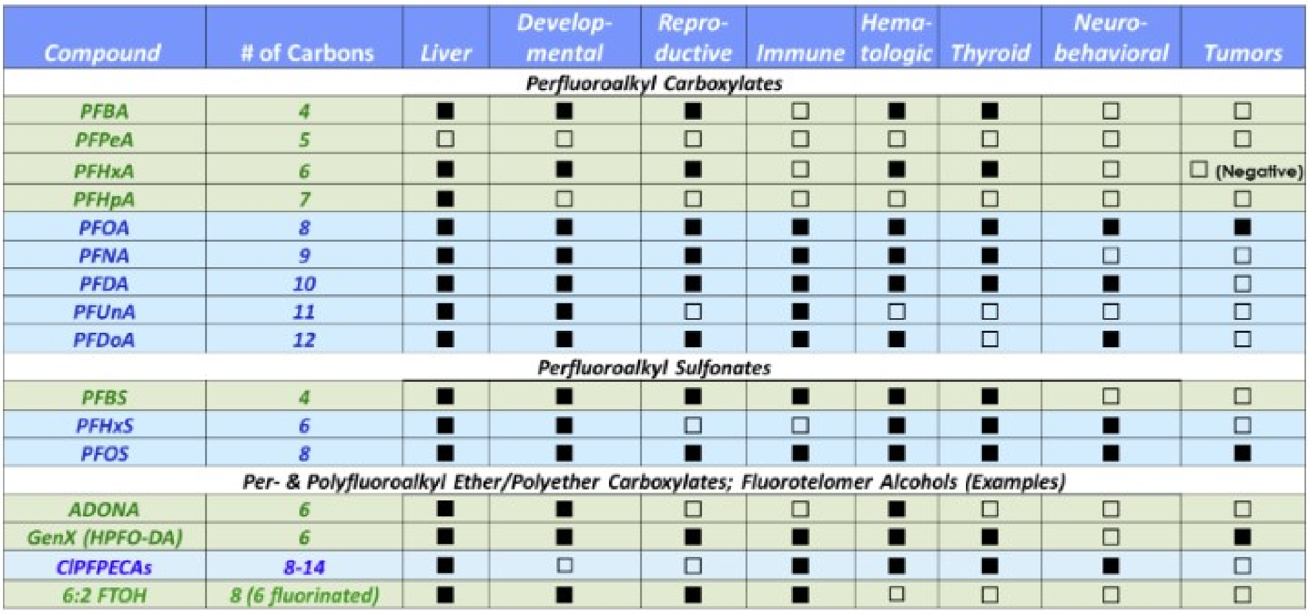
The overall potential for noncancer effects due to human exposure to more than one chemical is estimated using the hazard index (HI), which is computed as the sum of calculated chemical-specific hazard quotients (HQ). As explained by USEPA (1989), "This approach assumes that simultaneous subthreshold exposures to several chemicals could result in an adverse effect. It also assumes that the magnitude of the adverse effect will be proportional to the sum of the ratios of subthreshold exposures to acceptable exposures." Risk characterizations commonly produce initial estimates of HI by calculating the sum of all HQs. When the HI is estimated to be greater than 1, there may be potential concern for adverse health effects. However, when this initially estimated HI is greater than 1, refinement of the HI estimate by segregating HIs by effect and mechanism of action may be appropriate to support a risk management decision.

USEPA has developed a Draft Framework for Estimating Noncancer Health Risks Associated with Mixtures of Per- and Polyfluoroalkyl Substances (PFAS) (USEPA 2023). This document recommends assessment of noncancer health risks of PFAS mixtures based on dose additivity (for example, a hazard index [HI] approach). USEPA (2023) is the basis for a proposed MCLG and MCL of an HI of 1 for mixtures of four PFAS (PFBS, PFHxS, PFNA, GenX) (USEPA 2023). The draft MCLG and MCL use the "general" HI approach in which the HI considers toxicity values based on differing toxicological endpoints for the components of the mixture. More information on risk assessment of PFAS mixtures is found in Section 7.1.5.

As discussed in Section 7.1, several possible adverse health effects are associated with exposure to PFAS (Table 9-2). The type of information shown in this table can be used to segregate HIs by potential adverse effect in the risk characterization (i.e., the "Target Organ-Specific Hazard Index") when risks associated with exposure to specific PFAS are being evaluated and target organ-specific toxicity factors are available.

Table 9-2. Summary of potential noncancer health effects of various PFAS

Adapted from (ATSDR 2022)



Compound	# of Carbons	Liver	Develop-mental	Repro-ductive	Immune	Hema-tologic	Thyroid	Neuro-behavioral	Tumors
				Perfluoroalkyl Carboxylates					
PFBA	4	■	■	■	☐	■	■	☐	☐
PFPeA	5	☐	☐	☐	☐	☐	☐	☐	☐
PFHxA	6	■	■	■	☐	■	■	☐	☐ (Negative)
PFHpA	7	■	☐	☐	☐	☐	☐	☐	☐
PFOA	8	■	■	■	■	■	■	■	■
PFNA	9	■	■	■	■	■	■	☐	☐
PFDA	10	■	■	■	■	■	■	■	☐
PFUnA	11	■	■	☐	■	☐	☐	☐	☐
PFDoA	12	■	■	■	■	■	☐	■	☐
				Perfluoroalkyl Sulfonates					
PFBS	4	■	■	■	■	■	■	☐	☐
PFHxS	6	■	■	☐	☐	■	■	■	☐
PFOS	8	■	■	■	■	■	■	■	■
				Per- & Polyfluoroalkyl Ether/Polyether Carboxylates; Fluorotelomer Alcohols (Examples)					
ADONA	6	■	■	☐	☐	■	☐	☐	☐
GenX (HPFO-DA)	6	■	■	■	■	■	■	☐	■
ClPFPECAs	8-14	■	☐	☐	■	■	■	■	☐
6:2 FTOH	8 (6 fluorinated)	■	■	■	■	☐	☐	☐	☐

Notes:

The colors used for the PFAS names distinguish between short-chain PFAS (green) and long-chain PFAS (blue).
A filled-in (black) box indicates that the effect was reported in one or more laboratory animal studies. An empty box indicates that the effect was evaluated but not found, or effect has not been evaluated.

9.2 Ecological Risk Assessment

This section summarizes information that is currently available to conduct ecological risk assessment (ERA) of PFAS. The information presented is based on a review of current regulatory guidelines from within the United States and other jurisdictions, peer-reviewed publications, and other sources as noted. Sufficient information needed for performing ERAs exists only for some PFAS. When possible, discussions in this section indicate to which PFAS the discussions apply. Three recent publications funded by the US DOD, Conder et al. (2020), Divine et al. (2020), and Argonne (2021) discuss PFAS ERA in detail and provide a summary of much of the available data needed for conducting PFAS ERA within the U.S. These are the most comprehensive reports to date for completing PFAS ERAs within the U.S. The European Union (EU) also has a substantial amount of data available within their Environmental Quality Standards (EQS) for performing PFAS ERA, but the

EQS use different guidelines and approaches than those in the U.S. Use of these data will likely result in conflicting values and differing conclusions on data usability and adequacy for performing an ERA.

This section discusses challenges within three key components of ERA: ecological effects assessment, exposure assessment, and risk characterization. Conder et al. (2020) and Divine et al. (2020) are referenced throughout those discussions as applicable. In addition, a workshop sponsored by the Society of Environmental Toxicology and Chemistry (SETAC) was held in August 2019 and focused on the state-of-the-science supporting risk assessment of PFAS. A breakout group within that workshop focused specifically on ecotoxicology and ecological risks of PFAS. The expert panel in that breakout group produced a detailed manuscript describing the currently available information, data gaps, and uncertainties, and approaches to address these needs (Ankley et al. 2020). Like the Conder et al. (2020) and Divine et al. (2020) reports, the recommendations of Ankley et al. (2020) are also directly related to conducting PFAS ERAs and are mentioned here to provide readers an understanding of subjects that are relevant but that still have uncertainty so they can assess the importance of those subjects for their specific needs. Ankley et al. (2020) is referenced throughout this section as applicable. Additional recommendations from Ankley et al. (2020) not included later in this section are listed below:

- a need for prioritizing which PFAS to study and evaluate relative to ecological risk and toxicity
- environmental monitoring beyond PFOS and PFOA
- advancing the understanding of PFAS uptake, elimination, and bioaccumulation
- broader understanding of toxicity across taxa
- the use of new approach methods (often referred to as NAMs) and
- studying and assessing PFAS as mixtures.

The remaining text for this section is organized into three main components of ERA: ecological effects assessment, exposure assessment, and risk characterization.

9.2.1 Ecological Effects Assessment

Identification of ecological risk-based toxicity thresholds is a challenge for many PFAS. Toxicity data are available as discussed in Section 7.2. Some of these data have been used to establish thresholds as discussed below. Some major considerations for ecological effects assessment are identifying ecological screening thresholds, understanding ecological receptor variability, and evaluating ecological toxicity of mixtures. These are discussed in the following sections.

9.2.1.1 Ecological Screening Thresholds

The recently published manuscript by Ankley et al. (2020) includes a discussion of media-specific ecological screening thresholds that are available for certain PFAS around the world: PFOS, PFOA, PFBA, PFPeA, PFHxA, PFBS, and PFHxS. Ankley et al. (2020) did not claim the list of thresholds to be comprehensive of all ecological thresholds for PFAS around the world. The discussion here in this section presents thresholds that are included within that document with discussion relevant to ITRC’s intended audience. Ankley et al. (2020) can be referenced for a more detailed discussion and complete table of available thresholds from around the world.

U.S.—Federal Thresholds

USEPA has published draft national recommended aquatic life criteria for PFOA and PFOS in freshwater for public comment (USEPA 2022, 2022) and a fact sheet for the criteria (USEPA 2022). In addition, USEPA had published their responses to external peer reviews of the draft criteria (USEPA 2022, 2022). The draft criteria include acute and chronic water column values for freshwater environments and acute criteria for estuarine/marine environments. Tissue criteria are also proposed for whole body fish and benthic invertebrates and for fish muscle. These criteria are aimed at protection of aquatic life but are not protective of consumption by aquatic dependent wildlife (for example, birds and mammals foraging in aquatic environments). Currently, there are no ecological risk-based PFAS guidelines or media screening thresholds that are recommended by the USEPA for other PFAS.

In support of the Air Force Civil Engineer Center, Argonne National Laboratory developed ecological screening thresholds for surface water and soil (Argonne 2021). Values were developed for 4-, 6-, 8-, 9-, and 10-carbon linear PFCAs and the 4-, 6-, and 8-carbon linear PFSAs (see Section 2 for detailed naming conventions). The soil screening values are protective of terrestrial plants, invertebrates, and mammalian and avian wildlife. The surface water values are protective of aquatic life and aquatic dependent wildlife. Work was completed in consultation with Tri-Services Environmental Risk Assessment Working Group, and USEPA’s Ecological Risk Assessment Forum (Ankley et al. 2020).

There have also been a number of published studies and reports that follow U.S. federal guidelines (USEPA 1995) for developing aquatic life criteria. Giesy et al. (2010), Salice et al. (2018); Conder et al. (2020), and Divine et al. (2020) all calculated thresholds protective of aquatic organisms exposed to PFOS in freshwater environments, though these were published before USEPA released their draft criteria. Giesy et al. (2010) also reported a Tier II freshwater value for PFBS, while Conder et al. (2020) derived Tier I values for PFOS in both freshwater and marine environments and for PFOA for freshwater. Divine et al. (2020) developed Tier I freshwater values for PFOS and PFOA and Tier II values for 23 other PFAS. Tier I values meet the data required described in USEPA (1995) guidelines while Tier II values are developed with methods that incorporate uncertainty factors when the availability of required data is insufficient. Section 16.3 provides greater detailed discussion on the methods for developing thresholds protective of aquatic life.

U.S.—Thresholds for Specific States

Several states have established some criteria that are intended to protect aquatic organisms in their respective surface waters. The text below is not intended to be exhaustive and summarizes only some of the values that were available at the time this text was developed (Spring 2021).

In Michigan, AWQC have been established for PFOS and PFOA based on Rule 57 17 (MI EGLE 2019). This rule is based on the USEPA Great Lakes Initiative (USEPA 1995), which provides procedures and methodologies to derive numerical criteria that are protective of aquatic ecosystems. Rule 57 presents a two-tiered methodology in which Tier I procedures are essentially the same as the methods used to derive federal national water quality criteria (NWQC) (USEPA 1985) and Tier II procedures can be used to derive values where the full extent of the toxicity data requirements of NWQC are not fulfilled. Rule 57 presents procedures to develop three categories of numeric criteria—final chronic values (FCVs), aquatic maximum values (AMVs), and final acute values (FAVs)—which can be developed under either Tier I or Tier II. Due to the greater uncertainties associated with Tier II values, and given their lesser data requirements, these values tend to be more conservative than those derived with Tier I methodologies. The PFOA and PFOS numeric criteria for Michigan are all Tier II values due to the limited amount of peer-reviewed aquatic toxicity data. The final chronic values for the protection of aquatic life (flora and fauna) for PFOA and PFOS were 880 and 140 µg/L, respectively, while aquatic maximum values were 7,700 and 780 µg/L, respectively. In addition, the Michigan Department of Community Health (MDCH 2015) derived provisional PFOS surface water values for mammalian and avian wildlife based on Rule 57 guidance. The surface water avian wildlife value, based on eagles, kingfishers, and herring gull characteristics, was 0.035 µg PFOS/L. The mammalian wildlife value, based on otter and mink characteristics, was 0.084 µg PFOS/L.

The State of Minnesota has also derived several surface water criteria for the protection of aquatic biota. These values are based on guidelines in Minnesota Rules chapter 7050 (MR7050). Continuous chronic criteria for the protection of aquatic biota in surface water are available for PFOA (1,700 µg/L) and PFOS (19 µg/L) (Stevens and Coryell 2007; Stevens and Coryell 2007). Florida has established Provisional Surface Water Screening Levels that are in the same range as those for Minnesota: 1,300 µg/L PFOA in freshwater, 37 µg/L PFOS in freshwater, and 13 µg/L PFOS in salt water (FL DEP 2020).

In California, the San Francisco Bay Regional Water Quality Control Board (SFB RWQCB) has released Interim Final Environmental Screening Levels (ESLs) for PFOS and PFOA (SFB RWQCB 2020). These values were specifically developed for use within the jurisdiction of the specific water board, not the state of California, not the California Department of Toxic Substances Control, and not the entirety of the United States. Other jurisdictions may use these values, as is often the case with many published thresholds. However, with the number of different water boards in California, it is important to understand the applicability of these ESLs. These values include groundwater protection levels that are protective for direct exposure to freshwater and marine organisms, including rare, threatened, and endangered species. The values are based on a 99% protection level (lower 1st percentile of a species sensitivity distribution [SSD]) compared to a 95% protection level (lower 5th percentile of an SSD) used for a typical AWQC. There are also groundwater ESLs that are protective of adverse effects to birds and mammals from the consumption of aquatic prey (Table 9-3). These wildlife protection values (listed by the SFB RWQCB and in Table 9-3 as secondary poisoning ecotoxicity) are based on values published in Divine et al. (2020). Separate soil ESLs are included in the SFB RWQCB document that are protective of (1) plants and invertebrates or (2) birds and mammals. There are two soil ESLs for each chemical for both significantly vegetated and minimally vegetated areas for a total of four distinct values each for PFOS and PFOA as shown in Table 9-4.

Table 9-3. SFB RWQCB groundwater ESLs: Aquatic habitat ecotoxicity levels for PFOS and PFOA (SFB RWQCB 2020)

Table 9-3. SFB RWQCB groundwater ESLs: Aquatic habitat ecotoxicity levels for PFOS and PFOA (SFB RWQCB 2020)

Protected Organisms	PFOS (µg/L)	PFOA (µg/L)
Direct exposure ecotoxicity: Freshwater	0.56	540
Direct exposure ecotoxicity: Saltwater	2.6	540
Secondary poisoning ecotoxicity: Freshwater and saltwater	0.075	4.4

Table 9-4. Soil ESLs: Terrestrial habitat levels (SFB RWQCB 2020)

Protected Organisms	PFOS (mg/kg)	PFOA (mg/kg)
Significantly vegetated areas		
Plants and invertebrates	7.7	0.084
Mammals and birds (NOAEL-based)	0.013	0.57
Minimally vegetated areas		
Plants and invertebrates	33	0.84
Mammals and birds (LOAEL-based)	0.05	1.1

International Thresholds

Environment and Climate Change Canada (ECCC, previously known as Environment Canada) has proposed ecological Federal Environmental Quality Guidelines (FEQGs) for PFOS in surface waters, fish tissue, wildlife dietary values, and bird eggs (ECCC 2018). The PFOS threshold for surface waters was derived from a SSD based on long-term toxicity data that included data for amphibians, fish, invertebrates, phytoplankton, and macrophytes. The guideline to protect all aquatic life forms for indefinite exposure periods to PFOS in surface waters is 6.8 µg/L, and a whole-body fish tissue guideline value of 9.4 mg/kg wet weight (ww) was based on these fish data and bioaccumulation factors for bluegill from Drottar, Van Hoven, and Kruger (2002). The tissue threshold is intended for both freshwater and marine environments. It was not calculated with both food and water (direct media) BAFs, and thus it could be underprotective. However, Giesy et al. (2010) did use Drottar, Van Hoven, and Kruger (2002) data to calculate an acute no-effect threshold of 87 mg/kg ww whole-body fish. To protect mammalian and avian consumers of aquatic biota, ECCC derived wildlife dietary toxicity reference values (TRVs) using mammalian studies and avian chronic toxicity data. For mammals, the dietary value for PFOS was 4.6 µg/kg ww food while the avian dietary value was 8.2 µg/kg ww food. Based on the avian reproduction studies that were the basis for the dietary values, a guideline of 1.9 µg/g ww whole egg was also derived for PFOS.

Screening level assessment values have also been derived for PFOA (Environment Canada 2012). Environment Canada derived several predicted no-effect concentrations (PNECs) for PFOA for ecological species. PNECs are intentionally conservative concentrations of chemicals designed to represent a concentration at which no adverse effects are likely. These PNECs for PFOA were based on LOAEL values from a limited set of single organism toxicity studies adjusted with uncertainty factors. FEQG values are developed from a distribution of acute and chronic studies conducted on groups of organisms with an intent to be protective of a set percentage of organisms in that category (for example, a 95% protection threshold). Thus, these PFOA PNECs are not equivalent to FEQGs, though they still provide utility for screening level ERA. The PNEC for aquatic organisms, based on a study with the freshwater alga *Pseudokirchneriella subcapitata*, was 20 µg/L; a mammalian wildlife study based on cynomolgus monkey *(Macaca fascicularis)* derived a liver-based PFOA PNEC of 158 µg/kg ww. However, given the uncertainties associated with these values, care should be taken in their application to ERA. FEQGs for PFOA are currently under development by ECCC (ECCC 2018).

The Australian and the New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand (ANZECC/ARMCANZ) have established draft protective concentrations for freshwater organisms exposed to PFOS and PFOA. The values, as shown in Table 9-5, were developed by the Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE) (2018). Only the freshwater values have been adopted in the PFAS National Environmental Management Plan for Australia and New Zealand (HEPA 2020). The protocol for developing guideline values in Australia (Warne et al. 2018) includes some specifications for full lifecycle and multigenerational testing that were not sufficiently represented in the limited available marine studies. Instead, the freshwater values have been identified as interim thresholds for marine waters. The values from CRC CARE incorporated multiple studies and were based on SSD for each compound. The 90 and 95% protective thresholds for PFOS are 2.0 and

0.13 µg/L, respectively. These values are within the range of other published values (Giesy et al. 2010; Qi et al. 2011). A 99% protection value for PFOS was also proposed as 0.00023 µg/L, though this may be below ambient concentrations. It should be noted that the freshwater SSD and subsequent protection values are influenced by a multigenerational study (Keiter et al. 2012) with zebra fish (*Danio rerio)* that produced data that are noticeably lower than other data. Efforts to validate the data by repeating the study and its methods are ongoing at the US Army Corps of Engineers Environmental Research and Development Center (Gust et al. 2021). The ongoing work includes an expanded and more carefully determined dosing range, greatly increased replication base on statistical power analysis, expanded analytical chemistry with external validation, and an expanded suite of endpoints to improve overall toxicological context (Gust et al. 2021). All three of the PFOS protection values are taken from an SSD that includes studies on the low end that are well below the majority of other data points. Further, as indicated in table B3 of CRC CARE (2018), data used in the SSD include a mix of effect levels (EC10) and no-effect levels (NOECs). Thus, decisions based on these values should be made with careful consideration.

For PFOA, the 90 and 95% protective thresholds were 632 and 220 µg/L, respectively; these are similar to those derived in Minnesota and Michigan. Marine threshold values for PFOS were 32 and 7.8 µg/L for the 90 and 95% protective levels. For PFOA, the 90 and 95% protective thresholds for marine water were 14,000 and 8,500 µg/L, respectively. It is of note that the threshold values for marine species were at least 1–2 orders of magnitude greater than those from freshwater. Thus, one should take care in using freshwater toxicity data or threshold values when evaluating marine and brackish systems, given the apparent differences in species sensitivity between these two environments. Likewise, caution should be used if employing marine values to evaluate other PFAS for which there are no freshwater threshold values.

Table 9-5. Aquatic thresholds developed by CRC CARE (CRC CARE 2018)

Species Protection (%)	**PFOS (µg/L)**	**PFOA (µg/L)**
Freshwater		
80	31	1,824
90	2	632
95	0.13	220
99	0.00023	19
Marine		
80	130	22
90	32	14
95	7.8	8.5
99	0.29	3

A number of thresholds for PFOS are also available from the European Union (EU) as described in the Environmental Quality Standards Dossier (EQS) for PFOS (European Union 2011, 2013). These include maximum acceptable quality standards (MAC-EQS) for freshwater and marine ecosystems, and annual average quality standards (AA-EQS) for the same ecosystems. Standards are also available for secondary poisoning (that is, consideration of biomagnification through the consumption of contaminated prey). These values are shown in Table 9-6.

Table 9-6. Environmental quality standards (EQS) for PFOS (European Union 2011, 2013)

Category/Description	**Units**	**Value**
MAC-EQS (freshwater) (European Commission 2011, 2013)	µg/L	36
MAC-EQS (marine) (European Commission 2011, 2013)	µg/L	7.2
Pelagic Community EQS (freshwater) (European Commission 2011)	µg/L	0.23
Pelagic Community EQS (marine) (European Commission 2011)	µg/L	0.023
$QS_{biota, sec pois}$ (European Commission 2011)	mg/kg (ww)	0.033

Category/Description	Units	Value
$QS_{biota, sec pois}$ (freshwater) (European Commission 2011)	µg/L	0.002
$QS_{biota, sec pois}$ (marine) (European Commission 2011)	µg/L	0.00047
EQS (biota) (European Commission 2011, 2013)	µg/L	9.1
AA-EQS (freshwater) (European Commission 2011, 2013)	µg/L	0.00065
AA-EQS (marine) (European Commission 2011, 2013)	µg/L	0.00013
MAC-EQS = maximum acceptable environmental quality standard AA-EQS = annual average environmental quality standard QS biota, sec pois = secondary poison standard for concentration in fish tissue QS = quality standard EQS (biota) – environmental quality standard		

Other Considerations for Thresholds

A survey of reports from various regulatory agencies demonstrates that although ecotoxicity data are available for various PFAS, including PFBA, PFBS, and fluorotelomers (including 8:2 FTCA, 8:2 FTUCA, and several FTOHs), to date these typically consider only a few aquatic species that include *D. magna*, a green alga, and perhaps a fish species. Some regulatory programs (for example, USEPA 1985; Warne et al. 2018) require a robust data set covering several classes of organisms, and due to limitations in the number of classes of organisms represented in the published peer reviewed data, it is difficult to derive ambient surface water quality criteria for other PFAS (beyond PFOS and PFOA). Limited relevant toxicity data is a greater issue for terrestrial wildlife given that the only chronic, reproductive studies with two PFAS (PFOS and PFOA) that have been conducted to date are in two species, the bobwhite quail (*Colinus virginianus*) and mallard duck (*Anas platyrhynchos*). However, more data are becoming available for other PFAS (for example PFHxS and PFHxA) in avian laboratory models (Dennis et al. 2021). Importantly, no ecologically relevant studies have been conducted with mink or an adequate surrogate. As a result, the development of benchmark or threshold concentrations for wildlife and aquatic organisms has been slow but information is beginning to emerge.

Research on observed effects in benthic invertebrates and other benthic aquatic life with direct exposure to sediments contaminated with PFAS is limited. However, more recent literature is becoming available for sediment exposures (Marziali et al. 2019), there are no published benchmarks and publications are few. Research has focused more on aqueous exposure pathways. Observational data and monitoring have been used in some cases to develop an understanding of what exposure may be associated with effects. The Norwegian Pollution Control Agency (NPCA) established a sediment no-effect threshold of 220 µg/kg, a chronic toxicity range of 220–630 µg/kg, and an acute short-term effects range of 630–3,100 µg/kg (NPCA 2008; Bakke et al. 2010) for benthic invertebrates. The technical basis for the NPCA values relied on the principles of equilibrium partitioning (EqP) between sediment and surface water using a partitioning coefficient (Kd). Argonne (2021) also outlines this approach for determining site-specific sediment thresholds. The NPCA no-effect sediment value is based on a PNEC of 72 µg/L from a limited data set and an unspecified Kd. A sediment screening value of 6.7 µg/kg (wet weight) from the United Kingdom’s UK Environment Agency (2004) was also developed using EqP with a PNEC of 2.5 µg/L and a river sediment Kd of 8.7 L/kg. Simpson et al. (2021) have estimated sediment thresholds of 60 µg/kg PFOS and 250 µg/kg PFOS (both normalized to 1% organic carbon) protective of 99% and 95% of species, respectively, based on EqP using a Kd of 10 L/kg with an HC1 of 6 µg/L and HC5 of 25 µg/L. HC5 and HC1 are commonly established for contaminants from SSDs developed for the contaminant. These HCx (for example a HC5) represent the concentration above which the lower x proportion of species in the distribution may see adverse effects.

All of these sediment thresholds were reported for PFOS concentrations in marine sediments, though they provide some basis for screening level risk decisions for both marine and freshwater. Caution should be observed in using these values because associated effects, if any, are unclear, and the original work is not readily available. Caution should also be used in applying these NPCA sediment values from marine waters to freshwater because the freshwater organisms could be more exposed (as explained in Section 9.1.2) and either more or less sensitive than marine organisms. In its EQSD for PFOS, the European Union (2011) took the position that there is insufficient data available to confirm the need for a sediment quality standard and insufficient data to derive a threshold, thus electing not to develop a value. Similarly, a workgroup in northern Italy concluded that there was no need for a sediment environmental quality standard (EQS) for PFOA, PFBS, PFBA, and PFPeA and that data for a sediment EQS for PFHxA were insufficient (Valsecchi et al. 2017).

For soil, CRC CARE developed soil screening thresholds from SSDs for both PFOS and PFOA. The Canadian Council of Ministers of Environment (CCME 2018) has also developed several draft thresholds for PFOS in soil. A value protective of direct toxicity was developed from an SSD of plant and invertebrate IC25 values (the concentration at which a 25% reduction in a non-lethal biological measurement, such as growth or reproduction, occurs). Food chain models were used to develop values protective of soil and food ingestion by wildlife. CCME (2018) also developed a soil screening value protective of aquatic life for use at sites where off-site migration to nearby surface water bodies may be a concern. These values from CCME were issued draft for public comment, and final FEQGs have not yet been established. Soil threshold values for other PFAS, however, are limited.

9.2.1.2 Ecological Receptor Variability

Another major challenge with toxicity assessment for ERA is accounting for the large number of receptor types and the associated unknown variable sensitivity to PFAS. Although it is commonly understood that sensitivity to contaminants can vary widely across kingdoms or across classes of animals, the challenge for PFAS may be greater due to the lack of knowledge about this family of compounds. Studies have documented the presence of PFAS in various aquatic species since the 1950s (Danish EPA 2015; Giesy and Kannan 2001, 2002), such as bottle-nosed dolphins (Houde et al. 2006), seals (Butt et al. 2008), squid (Yang et al. 2012), alligators (Bangma et al. 2017), and polar bears (Smithwick et al. 2005; Smithwick et al. 2005; Greaves and Letcher 2013). The detection of PFAS within organisms is clear evidence of exposure. Unlike many other commonly detected contaminants, however, the availability of toxicological data for PFAS is limited relative to the broad range of organisms within which PFAS have been detected.

Standard ERA practice includes developing TRVs that consider measures of exposure and effects that could adversely impact populations of wildlife (for example, chronic studies on reproduction, growth, and survival). Mammalian studies on numerous sublethal endpoints (for example, systemic, immunological, developmental, respiratory, cardiovascular, gastrointestinal, ocular, hepatic) have been conducted for PFOS, PFOA, and other PFAS and are well described in the *Toxicological Profile for Perfluoroalkyls* (ATSDR 2021), but these are less commonly used for TRV development for ERAs. These sublethal, mostly systemic or organ function-based TRVs are really only used for ERAs in the absence of reproduction, survival, or growth data. Mammalian TRVs for the purposes of ERA can be developed for the majority of the Third Unregulated Contaminant Monitoring Rule (UCMR3) PFAS compounds listed in Section 8.2.2.2. Recommendations for selecting TRVs from available data for conducting ERAs are included in Divine et al. (2020), Conder et al. (2020), and Johnson et al. (2021). Avian oral dosing studies useful for ERA are less available. The dietary acute and chronic studies by Newsted et al. (2005); Newsted et al. (2007) examining PFOS exposure in mallard and bobwhite quail were the first published work relevant to ERA. Divine et al. (2020) and Conder et al. (2020) presented the data from their studies as well as data from other studies and for other PFAS that can be used for selecting avian TRVs. More recent publications relevant to ERA include that of Bursian et al. (2021), who looked at oral exposure of Japanese quail (*Cortunix japonica*) to PFOS, PFOA, and AFFF (both 3M and Ansul products), and (Dennis et al. 2020, 2021, 2021) who looked at northern bobwhite quail exposed to PFOS, PFHxS, and PFHxA. Newsted et al. (2005) and Molina et al. (2006) have also reported the results of bird egg injection studies using PFOS, while Cassone et al. (2012) and Norden, Berger, and Engwall (2016) have published in ovo studies with other PFAS. A caution with interpreting these egg studies is the uncertainty as to whether naturally accumulated concentrations have the same adverse effect as concentrations administered via injection in ovo. There also can be differences when measuring whole egg, yolk, or albumin (Custer, Gray, and Custer 2010). Finally, there is currently not enough data for modeling egg tissue concentration for these chemicals.

Reptiles are among the least studied vertebrate taxa in ecotoxicology (Hopkins 2000; Weir, Suski, and Salice 2010) despite contamination threatening reptile populations worldwide (Gibbons et al. 2000). A recent study (Furst, Weible, and Salice 2019) exposing brown anoles (*Anolis sagrei*) to PFOS and PFHxS provides data relevant to ERA. Measures of apical endpoints included decreased growth of juveniles exposed to PFOS, while exposure to PFHxS resulted in decreased egg viability in female anoles. To date, there are no other published reptile toxicity data available for any PFAS, although studies have shown PFAS tissue concentrations from some reptile species (Wang et al. 2013; Bangma et al. 2017).

Amphibian toxicity data are also limited, though more are available than are reptile data. Toxicity tests are available for eight different PFAS in the USEPA ECOTOX database and address exposure to four different species: the African clawed frog (*Xenopus laevis*), western clawed frog (*X. tropicalis*), Asiatic toad (*Bufo gargarizans*), and northern leopard frog (*Rana pipiens*)(USEPA 2019). A recent study (Flynn et al. 2019) is also available that looked at effects in American bullfrogs (*Rana* *catesbeiana*) exposed to a mixture of PFOS and PFOA. A laboratory bioaccumulation study (Abercrombie et al. 2019) of PFOS and PFOA in the eastern tiger salamander (*Ambystoma tigrinum*) and the American toad (*Anaxyrus americanus*) also provides some useful data for ERA.

For lower trophic-level organisms such as plants and invertebrates, toxicological data are typically generated through studies with direct exposure to spiked media. Studies are available to develop thresholds for use in ERAs, as has been done by ECCC (2018), CRC CARE (2017), Conder et al. (2020), and Divine et al. (2020). SSDs produced by CRC CARE (2017) showed lettuce to be more sensitive to PFOS than earthworms, but found the opposite occurred for PFOA. Divine et al. (2020) calculated Tier I water quality values for PFOS and PFOA, Tier II water quality values for another 21 PFAS, and soil screening values for plants and soil invertebrates for 6 PFAS each. Giesy et al. (2010) and ECCC (2018) generated PFOS SSDs for freshwater aquatic organisms, from which thresholds were derived. CRC CARE presented SSDs for PFOS and PFOA for marine waters and for soil to establish their thresholds. Giesy et al. (2010) noted that some guidelines for developing criteria from SSDs rely heavily on the four lowest effect concentrations; thus, results can be skewed if one genus or species is significantly more sensitive than others. In the freshwater SSD for PFOS generated by Giesy et al. (2010), C*hironamous tentans* (a species of midge) were 40 times more sensitive than the next most sensitive species, the fathead minnow (*Pimephales promelas*). However, the ECCC (2018) SSD does not show the same difference in sensitivity with a reported 14-day growth LOEC for Japanese rice fish (*Oryzias latipes*) below the *C. tentans* 10-day NOEC. For marine waters, fish are among the most sensitive organisms for both PFOS and PFOA as shown in SSDs (CRC CARE 2017), but they are more sensitive by just an order of magnitude or less. Additional studies by Simpson et al. (2021) and Hayman et al. (2021) have expanded the understanding of potential toxic effects in aquatic organisms in marine waters but an SSD that includes data from both of these studies has not been published.

SSDs have not been published for avian, mammalian, reptilian, or amphibian species. Although SSDs could possibly be generated for laboratory mammalian species exposed to some PFAS, data are insufficient to generate robust SSDs that are applicable to wildlife species. Mammalian SSDs would include mostly rat and mouse studies with a few monkey and rabbit studies. Extrapolation to other orders would be required. Existing data would be more conducive to an effects distribution because the number of species within the class of organisms would be so limited. A limited amount of published data is available for avian, reptilian, or amphibian animals, but these data are insufficient to determine a robust SSD or even an effects distribution.

Available toxicological data clearly do not adequately cover the range of organisms that are exposed to PFAS or within which PFAS have been detected, nor do the data have much breadth for chemicals beyond PFOS and PFOA. Sensitivity variation for aquatic organisms is evident from the SSDs, and likely sensitivity ranges for untested wildlife leave a clear knowledge gap for some or even most ERAs. However, this problem is not unique to PFAS. As with many other bioaccumulative and biomagnifying compounds, this knowledge gap can be addressed by using available data from surrogate organisms (for example, the closest taxonomic laboratory test species) and making some assumptions. The uncertainty in the potential difference in sensitivity needs to be acknowledged and discussed within ERAs. However, pending the outcome of quantitative analysis, risk conclusions and even risk management decisions are possible on a site-specific basis. Although extrapolations with surrogates is a common practice in ERA, caution should be used and decisions should be made in concurrence with regulatory agencies or other applicable stakeholders.

9.2.1.3 Ecological Toxicity of Mixtures

An additional major challenge in effects assessment for PFAS is considering the toxicity of mixtures. PFAS nearly always occur as complex mixtures in natural environments with multiple PFAS present at concentrations that vary by site and source of PFAS. At this time there are only limited data available to understand the toxicity of more than just a few chemicals based on single chemical exposure experiments such as direct toxicity to lower trophic level organisms or dietary exposures to upper trophic level wildlife. Thus, the ability to understand the toxicity of mixtures is limited by the scarcity of available toxicity data. However, in the absence of such data, several strategies using structural and physical properties and toxicity information from PFAS with available data may be helpful to infer potential mixtures effects, including mixtures with PFAS of unknown toxicity. These strategies include the use of in silico predictive techniques (for example, quantitative structure-activity relationships (QSARs)), using read-across from data-rich PFAS to inform data-poor PFAS, and estimating potential mixture risk using dose-addition risk assessment methods (for example, hazard index or relative potency factor approaches). Examples of published studies using QSAR for estimating PFAS toxicity include Hoover et al. (2019), Kovarich et al. (2012), and Cheng and Ng (2019) and additional citations within each of those publications. These studies typically evaluate an in vitro endpoint (such as cell death (Hoover et al. 2019)) or in silico measurements (such as the binding ability of known PFAS to specific cellular proteins (Cheng and Ng 2019; Kovarich et al. 2012) and then use QSAR to estimate how other PFAS would respond to that same endpoint or target. Similarly, Droge (2019) derived phospholipid membrane−water partition coefficients (K_{MW}) that were used within a model to predict induction of narcosis ($LC_{50,narc}$) and which could be used in the future with K_{MW}-QSARs.

Most of these studies aim to fill data gaps for individual PFAS. Since it is not yet clear how PFAS may cause toxicity to various ecological receptors, the applicability of these data to ecological risk assessment of mixtures is unknown. However, with additional chemical-specific data, methods for estimated combined toxicity, such as hazard index or relative potency factors, could then be applied. Caution should be used when applying any of these approaches; some of these methods are novel and others may be well established but are predicated on specific data-supported assumptions that have not been universally accepted. Standardized toxicity tests, such as those performed with terrestrial and aquatic invertebrates and plants, are available for performing controlled dosing experiments and for exposure tests with field samples containing natural mixtures. Laboratory dosing experiments with whole mixtures, mixtures of prioritized PFAS, or with specific formulations, and with exposure concentrations that bracket environmental relevance, are all needed to inform ecological toxicity of mixtures.

There are a number of ongoing research projects investigating simultaneous exposure of ecological receptors to multiple PFAS (primarily the UCMR3 chemicals) and their precursors, with these studies mostly using binary mixtures (Lee et al. 2017; Flynn et al. 2019; Bursian et al. 2021; Dennis et al. 2020; McCarthy et al. 2021). However, the relative toxicity, additivity, or synergistic effects of PFAS remain incompletely understood and still uncertain. McCarthy, Roark, and Middleton (2021) discussed some of the challenges with designing, conducting, and interpreting toxicity tests with mixtures of PFAS. The understanding of PFAS mixtures is still developing and there is little consensus in the scientific community regarding how to assess the potential adverse impacts of PFAS mixtures. Complicating a limited understanding of PFAS mixture toxicity is that both absolute and relative concentrations of PFAS mixtures will vary across sites and across time. Reliance on empirical data such as site-specific toxicity sampling or community structure studies ultimately may be needed to fully understand the potential impacts of mixtures.

9.2.2 Ecological Exposure Assessment

Detections of PFAS in tissues of top predators within both aquatic and terrestrial ecosystems (Section 6.5) points to ongoing exposure from bioaccumulative and possibly biomagnifying PFAS (Section 5.5.3). Thus, accuracy and realism within exposure and risk estimates for PFAS are important to making informed risk management decisions. With the challenges of accounting for multiple exposure pathways, building strong food web and ecological exposure pathway models is an important foundation of PFAS ERAs. Once completed, these models can be used to identify the key receptors and measures of exposure to complete the assessments.

For aquatic ecosystems, published data from laboratory studies and specific field sites are available that include both BCFs, BAFs, and biota-sediment accumulation factors (BSAFs). These values, some of which are discussed and presented in Section 5 and Table 5-1 (provided as a separate Excel file), can be used to model the measures of exposure for aquatic ecosystems. (Larson, Conder, and Arblaster 2018) used such data to conduct food chain modeling in four different avian receptors. Published values for fish are common; however, to date these values are not standardized in how they are reported (for example, wet versus dry weight; organic carbon or lipid normalization). Most importantly, these data are highly variant (Table 5-1); Environment Canada (2006) reported that field BAFs for PFOS in Canadian biota range from 6,300 to 125,000. Burkhard et al. (2012) reported that within published data sources (Giesy et al. 2010; Houde et al. 2006), laboratory and field bioaccumulation metrics usually do not agree. According to Burkhard et al. (2012), field-generated BAFs (wet weight tissue to field water plus some ingestion) for PFOS exceed BCFs (wet weight tissue to lab water) predicted in the laboratory. This is undoubtedly due to the inability or inaccuracy of laboratory models to account for both direct and food ingestion exposure pathways. LaRoe et al. (2017) pointed out that laboratory values include only accumulation across the gill membrane. Thus, ERAs are challenged with attempting to address both pathways. Larson, Conder, and Arblaster (2018) demonstrated that using environmentally relevant sediment concentrations with standard food chain models with both BSAFs and BAFs suggested sediment pathways may be underrepresented and studied. Although the combination of direct and ingestion pathways is primarily a challenge for aquatic systems, assessing risk to wildlife exposed to multiple media (for example, amphibians, semiaquatic wildlife) is also problematic. As noted by Divine et al. (2020), there are differences between the numeric value of BSAFs developed from field data versus laboratory methods, and also between values from laboratory studies using the same methods.

In addition to fish, accumulation values for benthic organisms (California black worm, *Lumbriculus variegatus*, Higgins (Higgins et al. 2007) and (Lasier et al. 2011); oysters, *Ostrea edulis*, (Thompson et al. 2011) and pelagic invertebrates (*D.*

magna), (Dai et al. 2013)) have also been reported. Example BSAF values from Lasier et al. (2011) for PFOS, PFOA, PFNA, PFBS, and PFHpA range from 7 to 49 kg sediment/kg tissue wet weight (as reported by authors). Divine et al. (2020) and Conder et al. (2020) summarized BSAFs for aquatic invertebrates and bivalves and for aquatic crustaceans for 15 PFAS. Both reports also discussed a variety of PFAS BAFs for amphibians, aquatic plants, benthic invertebrates, crustaceans, and fish. There is overlap, as well as difference, in the studies discussed and presented by Conder et al. (2020) and Divine et al. (2020). Much of this data is also described in Section 5.5. The Conder et al. (2020) report leans toward describing available data while the Divine et al. (2020) report goes a step further and attempts to apply the data to develop screening values from wildlife food web models, similar to the secondary poisoning values available in the EU (Table 9-6).

Data for terrestrial systems are limited to primarily plants (agricultural crops) and earthworms, with little available for vertebrate prey tissue. One exception is Müller et al. (2011), which published data for a soil-to-caribou-to-wolf BAF used by ECCC (2018) in establishing a soil threshold protective of terrestrial carnivores at 2.6 mg PFOS/kg soil. In nearly all cases, these BAFs and BSAFs are available only for PFOS, though the Lasier et al. (2011) study can be used to identify BSAFs for five of the six UCMR3 PFAS.

Caution should be used in applying any of the published bioaccumulation or biomagnification data for desktop exposure estimates that are in turn used to justify remedial action. Several factors and uncertainties are associated with performing desktop food chain modeling with the limited amount of published data. Some of these considerations include the following:

- differences in diets of receptors at investigation sites versus that of studies documented in the published literature: differences in the proportions of prey items; differences in the uptake and elimination rates of PFAS or overall bioaccumulation of PFAS by the prey
- differences in physiology between the site receptors and those in published literature: capacity and magnitude of transformation; metabolism and uptake and elimination rates of PFAS; the amount/composition of protein-containing tissues to which PFAS bind; species home range and migration
- differences in physiochemical properties of the abiotic media containing PFAS between investigation sites and published study sites: bioavailability and uptake of PFAS; environmental processes (photolysis, hydrolysis, microbial aerobic and anaerobic metabolism); the presence of precursors. There is not a sufficient set of bioaccumulation data to date to account for these variations. Such studies were part of the 2019 Statements of Need for Strategic Environmental Research and Development Program(SERDP) grant projects.

These uncertainties are not completely unique to PFAS, as there are many other contaminants for which risk assessments are performed. Though there is some uncertainty with desktop food chain models for PFAS based on abiotic media, quantitative modeling does not need to be avoided. Two conclusions should be reached through food chain modeling with abiotic media and literature based BAFs/BSAFs/BCFs: either concentrations at the site are sufficiently low such that it can be concluded that risk to the environment is negligible and acceptable or concentrations suggest further evaluation by either refined baseline problem formulation or a baseline ecological risk assessment (BERA). Conducting BERAs for sites with PFAS should not be substantially different from BERAs for sites with other chemicals. Either in situ or ex situ direct toxicity tests with representative organisms can and should be performed when exceeding the limited ecological risk thresholds that are available. Likewise, measured concentrations of PFAS in prey should be obtained if desktop food chain modeled exposure exceeds TRVs. But the biggest challenges for measuring PFAS in biota have to do with the unique analytical chemistry method issues (Section 11). Challenges such as selecting the correct biota to sample, matching the prey items to the diets of upper trophic level biota, or obtaining sufficient tissue volume for chemical analysis may exist, but these issues are not unique to PFAS investigations.

9.2.3 Risk Characterization

Some aquatic toxicity data are available for environmental risk assessment for a few PFAS, but wildlife data are still incomplete. Adequate, though not abundant, data are available for completing wildlife risk assessment, primarily for PFOS. The ability to complete risk assessments for other PFAS regularly analyzed and detected in environmental investigations (Section 6) is limited. However, with the exposure data discussed in Section 5.5 and Section 6.5, and methods discussed in Section 9.2.2, the foundations of a quantitative risk characterization can be completed for PFOS and to an extent, PFOA. Risk assessment for other PFAS can be made with some conservative assumptions and use of PFOS data as a surrogate. The ability to combine effects thresholds (Section 7.2) and exposures to characterize risk to environmental receptors is outlined in a few publicly available sources. McCarthy, Kappleman, and DiGuiseppi (2017), Conder et al. (2020), and Divine et al. (2020) have identified exposure factors and effects thresholds that can be used for completing quantitative ERA within current regulatory frameworks.

The risk characterization of any chemical has uncertainty associated with it, and ecological effects characterization for PFAS is no exception. However, at this time based on the data presented in this section, meaningful PFAS risk management decisions can be supported in some situations using the current state of ecological risk assessment science. Broad risk management decisions regarding the ecological risk of PFAS should not be made for most risk assessments. In some cases, with consideration of the knowledge gaps and uncertainties for the site-specific scenarios being evaluated, stakeholders can work together to reach defendable scientific management decisions. Such risk characterizations using non-site-specific abiotic media, surrogate information, and tools can form the basis of screening level assessments. These screening assessments can be used to make more informed decisions regarding the need for site-specific assessments, including the collection of site-specific tissue data. However, within these screening assessments, discussion of the uncertainties and data gaps and assumptions made should be included to inform the risk management decisions.

9.3 Uncertainty

In performing a site risk assessment, including information and a discussion regarding key factors of uncertainty in the risk characterization can be important. As noted by USEPA (1989), the source and degree of uncertainty associated with the risk characterization is needed to help decision makers (for example, risk managers, stakeholders), with sufficient level of detail to allow them to make informed risk management decisions (National Research Council 2009).

As noted throughout this guidance, while the science of characterizing and evaluating potential risks associated with PFAS exposure continues to develop, there are still uncertainties that arise in conducting site-specific risk assessments for sites with PFAS impacts. This section lists potentially critical uncertainties that, depending on the methodologies and assumptions used in a particular site-specific risk assessment, may warrant a discussion to help decision makers and stakeholders interpret and appropriately use the results of a risk assessment.

9.3.1 Fate and Transport

Site-specific risk assessments typically characterize risks associated with potential contaminant exposure that could occur currently or in the future. To characterize potential future exposures, conservative models are often used as tools to predict the fate and transport of chemicals in the environment. With regard to PFAS fate and transport, uncertainties can be introduced as follows:

- Estimating future environmental concentrations due to airborne wet and dry deposition (Section 5.3.2)
- Estimating the transformation of PFAA precursors to PFAA daughter end products (Section 5.4.2, Section 10.4.4) in the environment
- Modeling groundwater transport considering such factors as chemical-specific retardation (Section 10.4.1) and back-diffusion (Section 10.4.3.3)
- Estimating the bioaccumulation/bioconcentration of PFAS (Section 5.5.2, Section 9.2.1, Section 9.2.2) in a particular animal/plant or via food chain modeling

9.3.2 Human Toxicity

Human health risk assessments typically involve the use of toxicity values that are derived in a manner that is intended to represent a “reasonable conservative estimate” (USEPA 2012) of the dose-response in humans. Most of the toxicity values that have been derived by agencies for PFAS for use in site risk assessments are based upon animal studies, with human data used to support the hazard identification component of the risk assessment. However, it is noted that USEPA (2023, 2023, 2023), as well as CA OEHHA (2023) recently used human epidemiological data as the basis for draft noncancer toxicity factors (RfDs) for PFOA and PFOS and CSF for PFOA (Section 7.1.4). Additionally, there is a lack of toxicity values for many PFAS, which with their absence could result in an underestimation of the risks associated with PFAS exposure.

Overall, with regard to PFAS human toxicity, uncertainties in conducting a risk assessment can be introduced as follows:

- Missing dose-response information for site-related PFAS to which receptors could be exposed (Section 7.1, Section 9.1.1.2)
- Using toxicity values for a particular PFAS as a surrogate for another (Section 9.1.1.2)

9.3.3 Ecological Toxicity

As with human health risk assessments, ERAs often use TRVs that are generic and not site-specific. These generic TRVs are conservative by design because they are used for screening purposes (USEPA 2004). Likewise, there is a degree of conservatism incorporated into the derivation of generic criteria (for example, ambient water criteria) to account for uncertainty (Section 9.2.1).

Overall, with regard to PFAS ecological toxicity, uncertainties in conducting a risk assessment stem from using toxicological information from surrogate organism(s) to evaluate potential risks for organisms for which toxicity studies do not exist (Section 9.2.1)

9.3.4 Accounting for Nonsite-Related PFAS

Site-specific risk assessments rely on site characterization information (and as needed, modeling) to help estimate the amount of exposure receptors could be subject to currently or in the future. Given the widespread presence of PFAS in the environment (Section 6), including the potential of upgradient off-site PFAS impacts to migrate onto subject properties (Section 10.5), discerning “background” anthropogenic or off-site PFAS impacts at a site from site-related impacts can be challenging. To streamline risk assessments, it may be conservatively assumed initially that concentrations of PFAS are entirely site-related. Doing so, however, may overestimate the risks associated with site-related releases.

Updated September 2023.

10 Site Characterization

The PFAS Team developed a Production, Uses, Sources, and Site Characterization training video with content related to this section.

The intent of this section is not to present general site characterization principles, but to highlight unique considerations or examples for this family of emerging contaminants. It is assumed that site characterization will follow all applicable state and federal (for example, CERCLA or RCRA) guidelines. The general principles of site characterization are similar for PFAS as for any contaminant, in that the physical setting, release specifics, proximity to receptors, and fate and transport characteristics will determine the sampling locations and requirements. Because of the toxicity, persistence, mobility, ubiquity, the large number of compounds in this family of chemicals, the variability and uncertainty of specific compounds and their criteria being regulated, and the emerging nature of PFAS, it is necessary to consider specific concerns in PFAS site characterization efforts.

Section Number	Topic
10.1	Site Characterization Issues Relevant to PFAS
10.2	Initial Steps
10.3	Site Investigation
10.4	Data Analysis and Interpretation
10.5	Source Identification

Exposure to PFAS can occur through a variety of transport pathways involving all environmental media, as is described in Section 5. Because ingestion of water is deemed a major route of exposure in humans, and the emerging nature of PFAS as contaminants of concern, regulatory interest has in the past several years been centered on this pathway. In turn, this focus has led to an increased emphasis on investigation of the connection between drinking water sources and groundwater, including direct use of groundwater as drinking water and connections between surface water and groundwater. Because of this regulatory and investigatory focus, this section places more emphasis on characterization of groundwater plumes than characterization of other media. Although groundwater may have in the past been more commonly the initial regulatory and investigatory focus, regulatory focus is broadening to other media such as surface water and biota and as a site-specific characterization process advances data are generally required from one or more other media including soil, sediment, surface water, stormwater, air, biota, or other media depending upon the nature, duration, and time of the release. Section 2.2 includes detailed information about the wide range of PFAS chemistry. Section 4 includes information about physical and chemical properties.

The guidelines below include general considerations for the most common types of PFAS sites. Many of the papers referenced in this section are products of studies sponsored by SERDP/ESTCP. A list of SERDP/ESTCP research projects related to PFAS and AFFF can be found at https://www.serdp-estcp.org.

10.1 Site Characterization Issues Relevant to PFAS

Historical investigations may have missed the potential for PFAS contamination at a site because, until recently, these chemicals were not regulated, were not considered a health or environmental concern, or PFAS sampling and analytical procedures may not have been available. As a result, PFAS plumes had years to develop and migrate without detection or characterization. Reviewing available site information such as a timeline for processes, layout, chemical use, release history, and fire training and/or firefighting events when AFFF was used in comparison with the time period of PFAS use can be helpful in evaluating the types and potential occurrences of PFAS releases. Once the potential for a PFAS release(s) is reasonably established, initial sampling could be completed to verify whether PFAS is present. If PFAS is determined to be present at levels warranting further assessment, a site investigation would be completed to characterize the nature and extent of the release and subsequent PFAS distribution. However, a PFAS site may be one of the many without an identified source (ATSDR 2021).

The following are some important considerations specific to PFAS sites.

10.1.1 Evolving Science and Regulations

State of the science: Understanding of many aspects of PFAS, such as toxicology and behavior in the environment, is changing rapidly. This may require reevaluation of earlier assumptions and conclusions throughout the site characterization process.

Analytical methodologies: Analytical methodologies continue to be developed and improved. Specific attention must be paid to a wide variety of factors, such as analytical methods, detection/reporting limits, and parameter lists that are continuing to expand (see Section 11.2).

Sampling methodologies: Cross-contamination potential may exist due to the presence of PFAS in consumer products; many regulatory agencies require a precautionary approach to sampling prohibiting the use of materials that may be treated with PFAS. See Section 11.1, Sampling, for more details.

Regulatory environment: The regulatory environment remains in flux, with changing regulatory limits, sampling procedures, and compounds of interest. Investigators should review current regulatory requirements to identify impacts to the site characterization (see Section 8, and the Regulatory Programs Summary Excel file).

10.1.2 Source, Fate, and Transport Properties

Sources: PFAS sources are discussed in Section 2.6. AFFF releases are discussed in more detail in Section 3.3. In addition, Salvatore et al. (2022) proposed that PFAS releases to the environment could have occurred at AFFF discharge sites, industrial facilities included in 38 specific North American Industry Classification System (NAICS) codes, and PFAS-containing waste sites. There are also “secondary sources,” such as PFAS concentrating into one portion of a plume (for example, groundwater into surface water) that then acts as a source to further groundwater contamination.

Further, because of the large number and varying chemical and physical properties of PFAS, and widespread use of PFAS-containing products, there may be multiple locations that act as a source of PFAS at a site. In addition, PFAS are often detected at low levels in samples from locations without any apparent or nearby sources. In those instances, there may be a need to evaluate the site-specific anthropogenic ambient background concentrations and determine their contribution to PFAS concentrations in environmental media at a site. See, for example, Strynar et al. (2012).

Pathways: PFAS may be present or migrate via pathways that are not typically observed with other compounds. For example, PFAS may be present in groundwater at a site via air deposition and no direct on-site release.

Complex transitions between media: The behavior of PFAS in the environment may deviate greatly from typical contaminants. Transitions between media may be complex because of specific characteristics of these compounds. For example, PFAS may disperse more upon reaching the water table than is typical for most other compounds, or a groundwater plume discharging into a surface water body may infiltrate into groundwater elsewhere, with contamination in the surface water acting as a secondary source. See Sections 5 and 6 for additional detail.

Secondary Sources

Sources created through movement of contaminated media into an area that was previously uncontaminated (for example, contaminated water from irrigation wells or reuse and application of biosolids, or atmospheric deposition) or an area where physical or chemical processes have concentrated PFAS, resulting in an additional source (for example, multi-media interfaces; see Sections 5 and 6).

Partitioning: Because of their physical and chemical properties and the variability of those properties, certain PFAS may partition from water through different mechanisms (including hydrophobic effects, electrostatic interactions, and interfacial behaviors) to other media or forms, including air, micelles, foam, solids, NAPL, and interfaces between these phases. Physical and chemical properties are discussed in more detail in Section 4 and phase partitioning is discussed in more detail in Section 5.2 and as appropriate in several subsections in this section.

10.2 Initial Steps

Site-Specific Anthropogenic Ambient Background

Concentrations of PFAS present in environmental media at the site that are not the result of or influenced by site activities or releases.

A comprehensive initial assessment commonly starts with developing an understanding of potential PFAS uses in the area; history of the site operations that potentially used PFAS-containing materials; areas where fluorine-containing Class B firefighting foams were stored, used, or released; on-site or off-site air deposition patterns where PFAS may have been produced or processed (for example, manufacturer and/or industrial facilities that produce PFAS or use materials containing PFAS and are likely to have airborne emissions), and the regional geologic and hydrologic framework as it relates to contaminant transport to surface waters or drinking water wells. Following the initial assessment, several phases of site investigations may be required at a sufficient resolution to capture the effects of the heterogeneities that direct contaminant distribution, fate and transport, and remediation effectiveness. However, there may be a need to prioritize the evaluation of certain exposure pathways (for example, drinking water wells) during the beginning investigations to quickly assess potential human exposures and because of constraints on resources and schedule.

When historical PFAS releases have occurred upgradient of drinking water sources, drinking water sampling may be the first indication that there is a problem. In areas where there is a concern that a PFAS source may be present, identification and sampling nearby drinking water sources (for example, groundwater and surface water) have in certain circumstances preceded typical site investigation work and can be considered in future situations to determine if PFAS are present in potable water sources and evaluate the potential exposure to human receptors. In cases where sources are not well defined, reconnaissance sampling may be useful to inform the development of the conceptual site model (CSM) and site investigation. Prior to further site characterization, proper notification to consumers and evaluating options to reduce or eliminate PFAS exposures, including alternative drinking water sources, may be required. In cases where sources are not well defined, reconnaissance sampling may be useful to inform the development of the CSM and site investigation plan.

CSMs are useful tools for the presentation and evaluation of site characteristics, releases, contaminant fate and transport, and exposure pathways, and it may be appropriate to develop an initial CSM prior to or as a part of preparing a site investigation plan. Generalized CSMs are presented in Figures 9-1, 9-2, and 9-3. The referenced CSMs present most known and potential PFAS source areas, transport mechanisms, and pathways on a simplified physical setting. The CSMs also illustrate exposure routes and receptors.

CSM development is an iterative process over the project life cycle with information obtained during site investigation, remedy design, remedy implementation and optimization, and post-remedy monitoring (if applicable). Similar to the USEPA’s data quality objectives (DQOs), it relies on a systematic objectives-based site characterization process (ITRC 2015). The CSM for a PFAS site is developed with information on potential ecological and human receptors, and PFAS sources and releases (whether occurring on site or off site from groundwater, surface water, sediment, or air), and should be updated as new information becomes available through site characterization, evaluation of all pathways, and potential receptors. Because many PFAS sites have had releases of other contaminants and subsequent follow-up site investigations, it is possible that a CSM may exist for the site that could serve as the basis for modifications to address PFAS.

10.3 Site Investigation

This section highlights some important considerations for site investigation that are relevant for PFAS. The general principles of site investigation are similar for PFAS as for any chemicals.

10.3.1 Development of Site Investigation Work Plan

PFAS investigation work plans should take into consideration the information provided in this guidance document (for example, Sections 2, 4, 5, 6, 9, and 11), including items such as sampling procedures and equipment to prevent cross-contamination, analytical methods, compounds to be reported, quality assurance/quality control, geographically variable and changing regulatory requirements and criteria, site-specific environmental setting, human health and/or ecological risk assessment, and potential treatment technologies and remedial approaches (see Section 12). From a general perspective the work plan will depend on the type of PFAS source and subsequent transport via various media, both of which should be discussed in the CSM section of the work plan. Investigative approaches should consider potential nearby sources and secondary sources, such as irrigation, sludge, or biosolids applications; atmospheric deposition; landfill leachate; and wastewater treatment plant discharge. As noted below, it is critical for the investigation to generate data that directly support subsequent risk assessments, feasibility studies, EE/CAs, and/or other evaluations of potential remedial alternatives. For PFAS, this may require a relatively high data collection effort, given typical release scenarios (for example, as a mixture of different PFAS) and low criteria values, and require more than one phase of investigation.

10.3.1.1 Geologic and Hydrogeologic Investigation

Evaluation of the geologic and hydrogeologic framework associated with the site is critical, and sometimes that framework may need to be addressed on a regional basis, as the PFAS impacts may extend significant distances from the site.

The amount of information to be collected to complete an adequate assessment is a site-specific determination based on many factors, such as complexity of stratigraphic and lithologic variability, project objectives, and available budget. In development of a work plan, consideration should be given to understanding the geologic history and geomorphology of the site and to evaluating how the subsurface materials and geometry control the fate and transport of contaminants. High-resolution site characterization (HRSC) techniques are normally appropriate to obtain adequate subsurface information (for example, grain size, lithological interfaces, and high transmissivity zones) to complete stratigraphic assessments (USEPA 2016). ITRC has guidance on implementing advanced site characterization tools (ITRC 2019).

Environmental sequence stratigraphy (ESS) is also an approach that may be applicable depending on site-specific circumstances. ESS is a method for understanding the geologic framework and related subsurface contaminant transport pathways, both regionally and underlying a site. The ESS approach is presented in USEPA Groundwater Issue Paper “Best Practices for Environmental Site Management: A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models” (USEPA 2017). A case study describing the use of ESS for PFAS investigations is described in Section 15.1.3.

The geologic and hydrogeologic investigation should define the hydrogeologic and geochemical parameters that are pertinent to PFAS migration and applicable to subsequent remedial actions. A thorough understanding of site soil types (for example, f_{oc}, bulk density, surface charge, anion and cation exchange capacity, grain size, minerology, and water content) and geochemistry (for example, ionic concentrations, ionic strength, dissolved oxygen, oxidation-reduction conditions, and pH) is needed to assess PFAS transformation, partitioning (including desorption), and migration in groundwater or soil. Hydrogeologic parameters such as groundwater recharge, hydraulic gradient, infiltration rate, permeability, hydraulic conductivity, and seepage velocity are vital components of the site investigation and help define the potential migration rate of PFAS. A thorough evaluation of the site hydrogeology will aid in evaluating and designing remedial alternatives. For example, the site geochemistry, including cations, anions, total dissolved solids, and fouling parameters (for example, iron, manganese, hardness, biochemical oxygen demand (BOD)), as well as other organic compounds in groundwater, may have a significant impact on the selection, design, and implementation of potential groundwater remedies.

Similarly, understanding the range of concentrations of PFAS in varying soil types and PFAS distribution in the vadose zone compared to the saturated zone is an important objective of site characterization. At sites with soils of varying permeabilities, the PFAS distribution within these different soil types should be established to better understand the feasibility of various remedial options, such as those that involve amendment distribution within the subsurface. This type of information is also beneficial for documenting natural processes that may be contributing to retention of PFAS within source areas and influencing downgradient transport.

10.3.1.2 Surface Water Body Secondary Sources

Because certain PFAS are mobile and resistant to breakdown in the environment, there have been cases of surface water creating very large dilute groundwater plumes through recharge (ATSDR 2008). Infiltration of PFAS along the course of surface water systems, including tidal zones, may result in widespread secondary sources to groundwater, further enlarging the contamination area (Ju et al. 2008). A study assessing PFAS concentrations in river and groundwater from several locations found that concentrations and trends in groundwater were generally similar to those observed in surface water, suggesting the aquifer was contaminated with the same source as the surface water (Sharma et al. 2016). Areas with high hydraulic conductivity allow for the rapid spreading of PFAS over large areas. However, even in lower permeability geologic deposits, PFAS contamination is a problem because the combination of long groundwater residence times and persistence of most PFAS results in a long-time presence of these compounds in water resources (Banzhaf et al. 2017). In situations where PFAS-contaminated surface water is recharging groundwater, investigation of the potentially impacted groundwater should be conducted to fully characterize site-related contamination (Divine et al. 2023). Complicating surface water being a secondary source is that PFAS have been shown to concentrate at the surface water-air interface (Ju et al. 2008). PFAS contamination may also concentrate in naturally occurring surface water foam (due to an affinity to organic material in the foam and the higher PFAS concentrations at the surface water-air interface where the foam is formed). Therefore, site characterization must consider whether or not surface water bodies are the most downgradient extent of contamination. Section 5.3.4 includes information on transfer of PFAS between surface water, sediment, and groundwater, including how changing conditions in the hyporheic zone are likely to affect PFAS transformation and partitioning. A brief discussion of surface water–groundwater interactions extending the areal impact of PFAS contamination is discussed in a case study in Section 15.5, and surface water quality is discussed in Section 16.

When evidence suggests that PFAS contamination is being transported between surface water and groundwater, it may be important to identify site-specific conditions of the hyporheic zone and to quantify PFAS concentrations in sediments or porewater, mass flux between groundwater and surface water, and factors such as redox conditions, salinity, and composition of sediment or suspended particulates (organic and mineral content) that may affect PFAS sorption and transformation (see Sections 5.2.3 and 5.3.4).

PFAS levels in sediments can be an expression of the average deposition conditions of discharges that are episodic. Sampling of sediments on a dry-weight basis provides information on PFAS sorbed to sediments, but may underestimate or miss PFAS in mobile porewater, which makes passive porewater samplers practical tools to characterize the concentration and mass flux of PFAS in or across the hyporheic zone and correlate it with the sediment PFAS content. Some types of passive samplers allow accumulation of contaminants over time, thus generating a time-weighted mean concentration rather than a snapshot of concentration at a discrete time point as given by discrete porewater sampling. Therefore, depending on study objectives, passive sampling may provide data that are more representative of PFAS mass flux between surface water and groundwater as compared to sediment sampling or discrete porewater sampling. However, careful consideration of study objectives must be given when selecting the type of passive sampler, as equilibrium devices may not be appropriate for measuring episodic discharges. See Sections 11.1.7.4 and 11.1.7.7 for more information on porewater and sediment sampling for PFAS, respectively.

10.3.1.3 PFAS-Specific Tools for Site Screening or Characterization

Investigative techniques to characterize source soils and determine the three-dimensional extent of soil and groundwater contamination should be considered. HRSC technologies, while providing near real time subsurface lithological and hydrologic information, can be used to efficiently obtain discrete groundwater samples in the intervals of interest, such as the high transmissivity zones and lithological interfaces. Analytical procedures that can be used in a mobile laboratory and achieve ng/L detection limits are becoming more available and can be used on site in conjunction with discrete HRSC sampling techniques (Quinnan et al. 2021). Use of a mobile laboratory can be expensive and is cost-effective only in specific situations when a sufficient number of samples can be collected in a short time period to keep the mobile laboratory at or near its capacity. Use of a mobile laboratory and the quick turnaround of results they provide allow for adaptive selection of additional sampling locations for delineation or other objectives. One of the main drawbacks associated with current field-screening methods is the inconsistency of results associated with measurement sensitivity to site-specific factors, including varying soil types and compositions. Furthermore, field screening methods should not be anticipated to replace fixed-laboratory analysis in terms of satisfying regulatory requirements.

Other field-screening methodologies have either been tried or are in the research and development phase, including ion selective electrodes to quantify PFOS and a mobile field-screening unit for PFOS and PFOA, both of which are attempting quantification to ng/L levels (Deeb 2016). Another method in the development stage is “a synergistic approach for the targeted affinity-based capture of PFOS using a porous sorbent probe” (Cheng et al. 2020) that may be able to obtain a detection limit for PFOS in water at about 0.5 ng/L. Rodriguez et al. (2020) provided a review of PFAS-detecting sensors and expected future direction for sensors. Multiple technologies for PFAS site investigation including passive and no-purge samplers, passive flux meters, mobile labs, real-time sensors, and novel techniques for reliable detection in complex matrices have been recently reviewed (Horst et al. 2022).

10.3.2 Nature of PFAS Sources

The nature of primary and secondary PFAS sources at a site will largely determine the extent of PFAS contamination at the site. Multiple factors may contribute to the nature of PFAS sources at a site. Key factors to consider in development of a work plan include:

- Leaching from the vadose zone to the saturated zone: PFAS present in unsaturated soils due to retention mechanisms (for example, partitioning at the air/water interface and sorption to organic matter) are subject to downward leaching during precipitation or irrigation events (Section 5.2).
- Matrix diffusion: PFAS dissolved in groundwater that diffuses from higher permeability zones and accumulates in lower permeability silt/clay layers below the water table and may diffuse back into the higher permeability zones due to changing relative concentrations (Section 5.3.1).
- Desorption: PFAS resulting from desorption from solids in the vadose or saturated zones and resolubilizing in porewater or groundwater could occur when adsorption (that is, partitioning) is reversible (Milinovic et al. 2015); such desorption would have the effect of sustaining PFAS concentrations in porewater or groundwater.
- Nonaqueous phase liquids (NAPL) dissolution: PFAS entrained in NAPL in the subsurface may be associated with releases of chlorinated solvents and/or petroleum hydrocarbons.
- Other sources: Given the widespread use of some PFAS, additional sources upgradient or within a plume may be contributing to PFAS concentrations at a site. Collecting samples to allow for evaluation of anthropogenic ambient background and/or commingling of plumes may be necessary if it is suspected that other sources are a contributing factor.
- Atmospheric deposition: PFAS are sometimes associated with stack or other air-emission sources and may contribute to regional PFAS concentrations.
- Overland runoff: Runoff and stormwater conveyance systems can impact surface water locations downstream of the actual source or groundwater along the course of the conveyance system.
- Groundwater discharge to surface water or surface water recharge of groundwater: Gaining or losing surface water body (for example, rivers, streams, lakes, ponds, impoundments, and wetlands) conditions may influence the extent of a plume. Discharge or recharge (seepage) rates and directions may change seasonally, with extreme weather events, or during periods of drought or precipitation.
- Subsurface features, including utility lines: Preferential pathways may result from subsurface features. For example, flow may seep into or out of nonwatertight sewer lines based upon groundwater elevations relative to the utility. The bedding material of a subsurface line may also convey groundwater.
- Multicomponent mixtures: At some sites, numerous PFAS may be present in one or more source zones. Mixtures may be present for several reasons, including, but not limited to, the following: multiple sources, varying time frames, and a mixture of compounds introduced during production (Sections 5 and 10.5).
- Precursors: Delineating, as practicable, the extent of precursors that may degrade to PFSAs and PFCAs will help the investigator understand sources and potential long-term concentrations.

10.3.3 Extent of PFAS

As with other chemicals, a site investigation for PFAS relies upon understanding the nature of sources as well as the lateral and vertical extents. A PFAS release can be localized or highly extensive, both horizontally and vertically. The extent is a function of many factors, such as site conditions, the nature of the PFAS source, transformation of precursors, and the relevant migration pathways. For example, some PFAS may be highly mobile in groundwater and some PFAS plumes may have had many years to develop and could consist of many compounds that are not expected to degrade, as discussed above. Therefore, PFAS plumes could be larger or deeper than expected, although there are currently limited quantitative data on PFAS plume lengths or depths in groundwater as compared to other contaminants. Sufficient delineation of PFAS extent in groundwater requires a monitoring well network with wells located throughout the plume (for example, source area, midplume, distal end, side-gradient, and clean sentry wells to define the plume boundaries). Such a well network will provide data to evaluate dissolved phase migration, potential precursor transformation trends, and/or plume stability.

Detailed vertical delineation as a component of HRSC should consider soil sampling at predetermined depths and distinct lithologic units within the vadose zone, the zone of water table fluctuation, and beneath the water table to a depth necessary to determine the vertical extent of impacts. In addition, consideration should be given to groundwater sampling of all saturated units to an appropriate depth. Collection of these data may necessarily be an iterative process requiring more than one phase of investigation to determine the vertical extent of PFAS impacts. This information is beneficial for evaluating potential accumulation points, matrix diffusion potential, varying groundwater conditions, and risk assessment, and to support remedial alternative evaluation.

At sites where PFAS has been released to the subsurface and reached groundwater, the velocity of groundwater movement (advection) is a key consideration for understanding plume migration potential, as well as those processes that act on PFAS during advective transport (for example, sorption, diffusion). At some sites, more mobile shorter chain PFAS have been observed to extend relatively farther in groundwater than longer chain PFAS due to less retardation in groundwater. The partitioning behavior of PFAS is discussed in Section 5.2.

Another factor in the extent of PFAS at mature sites is prior remediation intended to address other contaminants. For example, groundwater pump and treat systems designed and operating to address other contaminants may have partially captured PFAS or their discharge may have spread PFAS. Other remediation methods such as oxidation may result in a change in the relative concentrations of individual PFAS (for example, oxidation of precursors).

Depending upon site-specific conditions, several pathways need to be considered to assess potential upgradient sources. PFAS migration in air from industrial or commercial sources can influence soil or groundwater a great distance from larger sources (Section 6.1), for example, see Barton (2010) and Shin et al. (2011). Data from urban soils and groundwater indicate that for sites near metropolitan areas, there may be measurable contributions of PFAS from other sources, unrelated to site-specific sources, see the site-specific anthropogenic background text box in Section 10.1.3 and Xiao et al. (2015).

Commingling of contaminants has a potential to impact PFAS extent (note that PFAS commingling with other contaminants could also affect several other facets of a site characterization and/or risk assessment). For example, for PFAS sites associated with industry, fire training, or emergency response that have a chlorinated solvent or other NAPL source, investigators need to consider potential effects on PFAS in the subsurface and related data collection requirements. Laboratory studies have demonstrated that sorption or partitioning of PFAAs may increase in the presence of trichloroethene DNAPL in bench-scale tests (McKenzie et al. 2016). Conceptual modeling of published PFAS data suggests that NAPL-water partitioning and NAPL-water interface interactions may significantly increase retardation of some PFAS in source zones (Brusseau 2018; Brusseau 2019; Brusseau et al. 2019, 2019; Costanza, Abriola, and Pennell 2020; Lyu and Brusseau 2020; Schaeffer et al. 2019; Silva, Šimůnek, and McCray 2020; Sima and Jaffe 2021). These enhanced attenuation processes are discussed in Section 5.2.4.1 (partitioning adsorption to air/water interfaces) and Section 5.2.5 (NAPL-water interface). This research suggests that if PFAS and NAPL are present in media that make effective source treatment unlikely—for example, in low-permeability soils or fractured rock—that fraction will represent a long-term contributor to groundwater plume persistence. At older sites where in situ (for example, oxidation) or pump and treat methods have been employed to reduce NAPL source areas prior to awareness of PFAS, those remedies may complicate characterization and distribution of PFAS. Depending upon the method employed, mobilization of some PFAS may have changed following treatment, and remedial actions may affect distribution and relative concentrations of individual PFAS (McKenzie et al. 2016; McGuire et al. 2014).

At most sites where PFAS is present in groundwater, the extent of PFAS contamination is likely to be a key objective for site characterization and used for identifying appropriate remedial options (if warranted). Estimating the plume advancement rate may provide beneficial information for the remedial decision process. For example, a plume that is advancing relatively slowly and without nearby receptors may be more amenable to different remedial approaches, such as in situ sorption or barrier-based approaches (see Section 12.2.4) or other less aggressive techniques (Newell et al. 2022), than plumes that are advancing rapidly towards nearby receptors. Determining plume stability (Section 10.4.8) and/or conducting contaminant transport modeling (Section 10.4.9) provide valuable data for assessing risk and evaluating remedial alternatives.

10.3.4 Investigation-Derived Waste (IDW)

How to handle IDW that contains PFAS is currently a complicated topic, with differing laws and guidance in different states that affect on-site management, storage, labeling, and off-site transportation requirements (ASTM 2021). Investigators must remain vigilant to identify current state and local requirements for IDW generated during site characterization efforts. Site-specific waste handling and disposal plans should be provided in the site's Health and Safety Plan (HASP), Quality Assurance Project Plan (QAPP), or Sampling and Analysis Plan (SAP) prior to waste generation. During a typical site characterization effort, IDW generated consists of purge water, decontamination water, soil, sediments, solids such as concrete and asphalt, single-use field equipment (for example, bailers, tubing), and personal protective equipment (PPE).

In general, industry has been using two methods to dispose of PFAS-containing solids IDW off-site: landfill disposal and thermal treatment. For liquid wastes containing PFAS, sorption treatment, thermal treatment, or underground injection has been used. On-site treatment of water IDW using existing aboveground treatment systems or temporary mobile units is another option. Treatment conducted on-site can minimize the volume of liquids requiring off-site disposal and may allow treated liquids to be discharged to a publicly owned treatment works or handled off-site as nonhazardous waste. As of March 2023, no PFAS meet the federal definition of a hazardous waste; therefore, most PFAS-impacted IDW is being disposed of as nonhazardous waste.

On December 18, 2020, the USEPA published a guidance document, Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances (USEPA 2020[]). This interim guidance document outlined IDW that contains PFAS, destruction and disposal technologies currently available and in use, considerations for vulnerable populations that live near these destruction and disposal sites, and current research on this topic. Its focus is on providing options that have the potential to destroy the C-F bonds (thermal treatment) or that control migration of PFAS (with landfilling or underground injection).

Several guidance documents exist for managing PFAS-impacted IDW at U.S. Department of Defense (DOD) installations, including U.S. Army, U.S. Navy, and U.S. Air Force sites. Therefore, any PFAS-impacted IDW generated from a DOD installation should follow the associated required procedures (USDOD 2018; USDOD 2020; USDOD 2020). State or local requirements may be more restrictive than the DOD guidance.

10.3.4.1 IDW Options

Thermal Treatment

Thermal treatment is a broad category that includes several heating technologies: hazardous waste combustors, nonhazardous waste combustors, carbon reactivation units, and thermal oxidizers. Incineration specifically has come under scrutiny recently for its potential to affect communities adjacent to and downwind of incineration facilities through stack emissions if the PFAS are not broken down completely and data gaps associated with the control of products of incomplete combustion (Schroeder et al. 2021; Stoiber, Evans, and Naidenko 2020; USEPA 2020; Galloway et al. 2020; Vollet Martin et al. 2022). Please note—the definition of "incineration" varies based on different state or federal regulations or guidance.

On April 26, 2022, the DOD issued a memorandum to temporarily prohibit the incineration of DOD PFAS materials, until DOD issues guidance on implementing the USEPA guidance on the destruction and disposal of PFAS. The DOD published a memo with interim guidance about destruction or disposal of materials containing PFAS on July 11, 2023 (USDOD 2023). A follow-up statement was published on July 17, 2023 about additional planning and coordination that is needed before incineration is implemented (USDOD 2023).

On June 8, 2022, Illinois passed a law that bans the disposal by incineration of any PFAS, including, but not limited to, AFFF. Incineration was defined as any burning, combustion, pyrolysis, gasification, or use of an acid recovery furnace or oxidizer, ore roaster, cement kiln, lightweight aggregate kiln, industrial furnace, boiler, or process heater.

Landfill

The practice of disposing of PFAS via landfill works to control contaminants of concern through containment. For PFAS and PFAS-containing materials, hazardous waste landfills or lined municipal solid waste landfills could be viable disposal options if the landfills are willing to accept PFAS IDW. Current landfills can serve as long-term containment sites for PFAS, but they are not explicitly designed to control and hold PFAS and PFAS-containing materials. The ability for landfills to safely contain PFAS and PFAS-containing materials is an active area of research by the USEPA and state regulatory agencies.

Subtitle C (hazardous waste) landfills have a bottom liner and leachate collection system, and have been used to contain PFAS IDW. The utilization of Subtitle D (nonhazardous, municipal waste) landfills to contain PFAS IDW is state-dependent due to the potential for leaching into the subsurface. However, there remain concerns with Subtitle C landfills regarding how to handle the collected leachate. Typically, landfill leachate is disposed and treated off-site at municipal wastewater treatment plants, where the leachate is mixed with wastewater and then treated. However, a landfill that contains elevated PFAS in the leachate presents a difficulty for treatment. In addition, research has found that soluble PFAS with high vapor pressures can be emitted into the atmosphere via the gas generated at landfills (Ahrens et al. 2011; Hamid et al. 2018; Wang et al. 2020; Weinberg, Dreyer, and Ebinghaus 2011). This is an active area of research. Due to these concerns, not all Subtitle C landfills will accept PFAS wastes.

Deep Well Injection

Underground injection could be an option for liquid PFAS IDW. Disposal using this technology occurs under USEPA's underground injection control (UIC) regulations.

The UIC regulations give the USEPA the authority to permit the disposal of PFAS and PFAS-containing liquid IDW in Class I underground injection wells. Class I wells in either the nonhazardous or the hazardous waste categories are designed to dispose of and isolate liquid PFAS and PFAS-containing IDW. Class I underground injection wells are deep injection wells that inject the liquid of concern into a stable geologic formation below the lowermost underground sources of drinking water (USDW).

Underground injection to Class I nonhazardous and hazardous waste wells reduces the risks associated with surface-based disposal methods by avoiding a potential discharge of liquid IDW to surface and shallow groundwater and generating little to no air emissions of PFAS. Class I wells must be sited in areas that are geologically stable without the presence of natural fractures and faults that could allow the injected material to migrate into USDWs (DeSilva 2019; Marine 2020; McCurdy 2011; USEPA 2001; USEPA 2015).

Other/Developing Technologies

Additional methods, and methods in development for disposing of PFAS and PFAS-containing materials, are discussed in Section 12, including in situ and ex situ disposal methodologies for both soil and liquid PFAS and PFAS-containing IDW.

10.3.4.2 Other Considerations

PFAS IDW may also contain other commingled nonhazardous or hazardous substances. This will impact the options available for handling and disposal and should be considered during the project planning process. Of particular concern are wastes from sites where incineration of PFAS is not permitted that have co-contaminants usually disposed of through incineration (such as Toxic Substances Control Act wastes). In these cases, site managers may need to weigh the site characterization needs against the IDW disposal requirements and avoid generation of co-contaminated wastes.

10.4 Data Analysis and Interpretation

There are a number of approaches, methods, and tools available for analyzing and interpreting site characterization data from a wide range of contaminated sites. Examples of approaches, methods, and tools that may be relevant to PFAS sites are described below, but site-specific objectives and characterizations should be considered when determining an appropriate approach.

10.4.1 Vadose Zone Leaching

Recent research has illuminated the complexities of PFAS fate and transport in the vadose zone. The majority of this work has focused on lab-based or modeling studies, with an effort to understand how PFAS surfactant properties can enhance or reduce PFAS sorption, in particular at high concentrations such as those encountered at release locations (Sections 5.2.2.2, 5.2.3, and 5.2.4.1). As indicated in Section 5, soil chemistry plays a major role in PFAS fate and transport.

For example, Guo, Zeng, and Brusseau (2020) conducted a sophisticated modeling study indicating that PFOS in the vadose zone at a hypothetical fire training site is primarily sorbed at the air-water interface and only 1–2% of PFOS is in the aqueous phase under the modeled conditions (see Section 5.2.4). This indicates that strong PFOS attenuation may occur in the vadose zone over time, although Guo, Zeng, and Brusseau (2020) showed that eventually there still may be discharge of PFOS to the underlying water table under their modeled conditions. This is consistent with high concentrations of PFOS observed at some fire training sites. Rovero et al. (2021) reviewed literature-reported sorption coefficients (Kd) of eight anionic short (C4)- to long- (C10) chain PFAS, including PFOA and PFOS. Given the broad range in Kd values from 3 to 5 log units, no single value seemed appropriate for estimating PFAS leaching using existing soil-water partition equations. Regression analysis was used to determine if any of the fifteen experimental parameters identified in the literature might be used to predict Kd values. The authors found that none of the values could individually explain variability in reported Kd values, but significant associations existed between Kd and soil calcium and sodium content, suggesting that soil cation content may be critical to PFAS sorption. Organic carbon was found to only be significant at elevated levels (>5%).

Zeng and Guo (2021) developed a three-dimensional model to evaluate the effects of surfactant-induced flow and heterogeneity on PFAS leaching in the vadose zone. Based on simulations using this model, they found that: 1) surfactant-induced flow had little impact on long-term PFAS leaching; 2) subsurface heterogeneity led to preferential flow that results in early arrival and accelerated leaching of PFAS; and 3) acceleration of PFAS leaching in high water-content preferential pathways or perched water above capillary barriers was more prominent than for conventional contaminants due to destruction of air-water interfaces (reduction of air-water interfacial area (A_{aw})). The authors of this study also recommended that multidimensional models be used to predict PFAS leaching in heterogeneous soils. Note that these conclusions were based on modeling results, and validation of the results using field data was beyond the scope of the study.

Modeling can be used to try to simulate PFAS transport in the vadose zone; however, it should be performed with careful selection of input values and should note appropriate caveats (see Section 10.4.9). For example, parameters that are important to understanding PFAS leaching processes, such as the air-water interfacial area (A_{aw}), may be challenging to estimate and/or not adequately captured using current models.

Analytical leaching methods such as the Synthetic Precipitation Leaching Procedure (SPLP) [SW-846 Method 1312 (USEPA 2021)] and the Toxicity Characteristic Leaching Procedure (TCLP) [SW-846 Method 1311 (USEPA 2021)] may be able to provide site-specific insight into the leachability of PFAS from vadose zone materials. The TCLP "is designed to determine the mobility of both organic and inorganic analytes present in liquid, solid, and multiphasic wastes" for waste characterization purposes (USEPA 2021). The SPLP is designed to determine the mobility of both organic and inorganic analytes present in liquids, soils, and waste to evaluate the potential of contaminants to leach into groundwater (USEPA 2021). Therefore, the SPLP is typically used for soils in site characterization contaminant leaching studies and allows for less acidic extraction fluids (simulating exposure to acid rain) than the TCLP test (simulating exposure in a landfill) so it can better represent environmental conditions expected to be encountered at a site. Currently some state agencies include the SPLP test as part of their PFAS assessment guidance, so state-specific guidance or requirements should be verified.

USEPA has also developed a Leaching Environmental Assessment Framework (LEAF). LEAF is a leaching evaluation framework consisting of four leaching tests (SW-846 Methods 1313, 1314, 1315, and 1316), a data management tool, and approaches for estimating constituent releases from solid materials (USEPA 2019). The four leaching tests discussed have been validated for inorganic constituents, but the methods and/or framework may be helpful when evaluating leaching of PFAS in the environment.

Optimizing LEAF leaching tests for use with PFAS is one component of an in-progress SERDP-ESTCP sponsored study: Development and Validation of Novel Techniques to Assess Leaching and Mobility of Per- and Polyfluoroalkyl Substances (PFAS) in Impacted Media, ER20-1126 (SERDP-ESTCP 2021). The project overview states that the study has the overarching goal of developing a framework for evaluation and prediction of the release of PFAS from AFFF-impacted media. Identified specific objectives include: 1) development of a standard leaching assessment methodology for AFFF-impacted media; 2) utilization of approaches including high-resolution mass spectrometry (HRMS), mid-infrared spectroscopy (MIR), and chemometrics to evaluate and develop a predictive model of PFAS sorption and desorption to AFFF-impacted media; and 3) comparison of results of laboratory testing to leaching and mobility under field-relevant conditions to develop an approach for translation of bench-scale test results to site-scale implications. Other SERDP-ESTCP sponsored studies include ER20-5088, which is evaluating how PFAS leaching is influenced by factors such as the soil to groundwater ratio (PFAS Leaching at AFFF-Impacted Sites: Insight into Soil-to-Groundwater Ratios), and ER18-1389: Baseline Data Acquisition and Numerical Modeling to Evaluate the Fate and Transport of PFAS within the Vadose Zone.

Many studies describe the complexity of soil retention mechanisms for an increasing number of nonpolymeric PFAS. This complexity is due to multiphase retention mechanisms that can include air-water interfacial sorption mechanisms as well as both hydrophobic and electrostatic interactions with the surface chemistry of soil particles (Sima and Jaffe 2021; Sharifan et al. 2021; Guelfo et al. 2021). In addition, studies have demonstrated rate-limiting solid-phase sorption kinetics (Brusseau et al. 2019), nonlinear sorption to both solids and air-water interfaces (Schaefer et al. 2019; Li et al. 2019), and desorption hysteresis (Zhao et al. 2014; Ololade 2014; Schaefer et al. 2021). Solution chemistry effects have also been shown to affect retention processes (Cai et al. 2022). All together, these multiphase retention mechanisms may complicate efforts to accurately predict long-term leaching potential from legacy source zones.

Stahl et al. (2013) completed a study evaluating the behavior of PFOA and PFOS in soil and the carryover from soil to plants. Plant samples and percolated water collected by a lysimeter were analyzed for PFOA and PFOS throughout a period of 5 years. PFOA was found to pass through the soil much more quickly than PFOS, and of the original mass applied, 96.88% of the PFOA and 99.98% of the PFOS was still present in the soil after a period of 5 years. Plants were found to have accumulated 0.001% of the PFOA and 0.004% of the PFOS. Loss through the soil leachate was reported to be 3.12% for PFOA and 0.013% for PFOS.

Given the complexity of estimating the mass discharge of PFAS from vadose soils to groundwater, care should be taken when selecting an approach(es) to estimate PFAS leachability to ensure it is appropriate for the site's physical environmental setting, and consideration should be given to developing multiple lines of evidence. Further, because of the limitations and uncertainties of the available estimation tools, care should be taken when evaluating and interpreting results. Currently available tools to consider include leaching methods (for example, SPLP or LEAF) as discussed above, modeling as discussed in Section 10.4.9.1, and soil lysimeters discussed below and in Section 11.1.7.5. Applicable regulatory guidance and requirements should also be considered.

Like grab samples, lysimeter samples represent a single-time result, which makes the representativeness of lysimeter results suspect when evaluating impacts to groundwater over a season or from year to year. Suction lysimeter samples are good for qualitative comparisons, but they cannot be used for quantitative analysis unless the variabilities of parameters involved are established (ASTM International 2018).

Collection of porewater data via lysimeters may provide pertinent empirical data for one line of evidence for qualitatively evaluating site-specific leaching of PFAS from the vadose zone to the groundwater. Anderson (2021) completed systematic measurements of porewater PFAS concentrations using lysimeters installed within relevant portions of a site. Mass discharge was estimated by multiplying observed lysimeter porewater concentrations by estimated vadose zone infiltration rates to determine the mass of PFAS leaching from the vadose zone to groundwater. However, lysimeter data may be biased by factors such as preferential flow, and samples may not be representative in dry or wet conditions. Isch et al. (2019) completed a study of water and bromide in bare soil using lysimeters compared to field plots and found that the transport of water and bromide in bare soil observed in lysimeters could not be directly compared to their transport observed in field plots. Radolinski et al. (2022) completed a study using lysimeters of how preferential flow alters solute mobility in soils and found that there was "evidence that (1) bypassing water flow can select for compounds that are more easily released from the soil matrix, and (2) this phenomenon becomes more evident as the magnitude of preferential flow increases."

Lysimeters have been suggested as a tool that can be used to measure the mobile mass fraction of PFAS concentrations in soil porewater (Anderson 2021). Lysimeters have been used by researchers investigating transport of AFFF at impacted field sites to benchmark the accuracy of laboratory batch extraction methods (Schaefer et al. 2022; Quinnan et al. 2021) and to understand temporal trends in PFAS concentrations in porewater (Anderson et al. 2022).

Fate and transport processes can have differential impacts on the individual components of chemical mixtures such as PFAS (see for example, Bock et al. 2022). Differences in the fate and transport process affecting chemical mixtures can result in changes in the relative abundance of these components. For example, more easily transported PFAS in a mixture could be preferentially leached in the source area and enriched downgradient. These processes should be considered when evaluating fate and transport, as well as when conducting a forensics evaluation of PFAS. It should be noted that chemical transformations, such as the conversion of PFAS precursors, will also result in changes in the relative abundance of PFAS in a mixture. These processes emphasize the importance of developing accurate estimates to predict the behavior of PFAS, including PFAS behavior in the vadose zone.

10.4.2 Retardation Coefficients and Travel Time in Groundwater

The time that it takes for a contaminant in groundwater to travel to a particular downgradient location is highly influenced by the groundwater velocity, and the plume extent is further influenced by processes that may act on the contaminant during transport, as well as by physical chemical properties of the contaminant itself (for example, solubility). As an initial step for evaluating PFAS transport, it may be helpful to estimate retardation coefficients for PFAS to evaluate contaminant-specific velocity and travel time in groundwater, particularly for longer PFAS plumes. As discussed in Section 5.2.3, a linear sorption isotherm is typically assumed for PFAS sorption to organic matter in soil, and sorption coefficients. The Physical and

Chemical Properties Table (Table 4-1) provided as a separate Excel file presents a range of available organic carbon partitioning coefficients for environmentally relevant PFAS. Hydrophobic, electrostatic, air-water sorption in the vadose zone, and hydrophobic and electrostatic sorption in the saturated zone also play a role in transport mechanisms (Newell et al. 2021).

However, as noted in Section 5.2.3, it is important to evaluate the PFAS present and quantify the fraction of organic carbon for estimating K_{oc}. The current state-of-science supports K_{oc} being reported in relatively broad ranges on a compound-specific basis. Section 4.2.9 presents a discussion of potential limitations in using K_{oc} values as a predictor of sorption and PFAS mobility. It is also important to note that other geochemical factors (for example, pH, presence of polyvalent cations, and electrostatic processes), possible hysteresis, and nonlinear sorption behavior might influence transport across different PFAS concentration ranges, and isomeric differences may impact PFAS sorption to solid phases (Section 5.2.3). Due to the variability of K_{oc} estimates, it may be appropriate to evaluate transport of an individual PFAS using a range of partitioning coefficients. In addition, empirical estimation of site-specific K_{oc} values in different areas of a site (for example, source zone versus downgradient plume) may be necessary if quantification of the retardation coefficient is important to its characterization.

For example, McGuire et al. (2014) described the calculation of site-specific K_{oc} values for various PFCAs and PFSAs at an AFFF-impacted site. These site-specific Koc values were calculated based on seven pairs of co-located groundwater and soil samples, and fraction of organic carbon (f_{oc}) measurements at each sampling location. The soil samples were collected near or at the water table, which was about 4.6–6.1 m below ground surface. McGuire et al. (2014) found that there was a range of between one and three orders of magnitude in site-specific K_{oc} values for the PFAAs analyzed. This may reflect the enhanced sorption of PFAS that occurs at the NAPL-water or air-water interface (Brusseau 2018). There may be smaller ranges in K_{oc} values for PFAAs at greater depths below the water table and downgradient of a source zone (where NAPL is not present). When using this type of site-specific K_{oc} analysis method, it is also important that the groundwater samples be representative of conditions where the point soil samples are collected.

As another alternative to the use of K_{oc} values and the assumption of a linear sorption isotherm, in situ or ex situ studies may be used to develop parameters for simulation of PFAS transport. Such studies could allow development of pseudo-constants to use in model simulations. In groundwater, a bulk retardation factor can be estimated by comparing the observed length of a PFAS plume to the distance that groundwater would be expected to travel during the time since the PFAS release occurred. This method provides an estimation and assumes that the release date is known, but it accounts for the multiple processes influencing PFAS migration in groundwater (as opposed to just hydrophobic partitioning to soil organic carbon).

Desorption of PFAS from solids below the water table could occur when partitioning is reversible; such desorption would have the effect of maintaining PFAS concentrations in groundwater. There is uncertainty regarding the extent to which sorption is irreversible and rate-limited versus an equilibrium process (Section 5.2.3). It may be important to characterize the extent and kinetics of desorption that may occur as a result of remedial activities at the site. Assuming equilibrium desorption may result in overestimation of PFAS removal during remediation activities (Sima and Jaffe 2021).

Because retardation coefficients, travel time, and many other fate and transport processes are based on the physicochemical properties of the individual PFAS, these processes may not affect all PFAS in a mixture equally. As predicted for PCBs in Johnson and Bock (2014[2521]), in which aggressive physical weathering was simulated, differential fate and transport trends affecting the components of a chemical mixture can manifest as changes in the chemical profile. For PFAS, more easily transported PFAS in a mixture could be depleted in the source area and enriched at the plume front. A simple model demonstrating the effect for PFAS mixtures based on Koc and foc using the RemChlor-MD model (Farhat et al. 2018) from Bock et al. (2022) predicts that these processes can have important ramifications for PFAS forensics.

10.4.3 Matrix-Diffusion

When evaluating fate and transport of PFAS in a groundwater plume, including time frame for remediation of PFAS, matrix diffusion may be an important process to consider (Section 5.3.1). As such, understanding the potential impacts of diffusion on PFAS persistence in natural soils is a topic of ongoing research.

During the characterization of PFAS plumes, it may be beneficial to collect PFAS soil samples from the transmissive zone directly above a silt/clay layer, and at different depths into the silt/clay layer, to evaluate the potential for back-diffusion to be occurring presently or in the future if there is a decline in PFAS concentrations in the transmissive zone (see Parker, Cherry, and Chapman (2004) and Chapman and Parker (2005) for an example of this sampling approach). Using this approach, Adamson et al. (2020) reported that the majority of the PFAS mass at an AFFF release site was associated with lower permeability soils, highlighting the importance of matrix diffusion on PFAS retention.

Diffusion coefficients for PFAS are generally uncertain but are in development using measurements and models (Pereira et al. 2014). Schaefer et al. (2019) calculated aqueous diffusivity values for nine PFAAs; however, prediction of the influence that diffusion from lower permeability material to a flow zone (i.e., back-diffusion) will have on PFAS remediation time frame remains uncertain because the back-diffusion of PFAS from low-permeability materials involves desorption. As discussed above, PFAS desorption may be a rate-limited process, and these rates have a high degree of uncertainty (Sima and Jaffe 2021). In addition, the irreversible fraction of PFAS in low permeability materials is uncertain at this time. Therefore, the uncertainty associated with modeling remediation time frames of PFAS back-diffusion should be noted. Further discussion of matrix diffusion modeling is included in Section 10.4.9.

10.4.4 Mass Flux/Mass Discharge

Mass flux and mass discharge can be valuable metrics for CSMs and understanding PFAS transport and supporting remedy selection. ITRC (2010) presented a variety of methods available for estimating mass flux and mass discharge, including the use of multiple transects of temporary or permanent monitoring wells across the width of a plume. Even simple methods such as chemical isoconcentration maps are suitable for developing an initial order of magnitude estimate for mass discharge. Calibration of solute transport models is another method that may be used to estimate the mass discharge of PFAS from a source zone, at a point in a plume, or to a surface water body. In addition, mass discharge estimates may be useful for understanding PFAS exchange between groundwater and surface water (Divine et al. 2023), and PFAS retention at the air-water interface could be an important fate and transport process (see Section 5.3.2) and may be considered when estimating the mass discharge from the vadose zone soils to groundwater. See Section 10.4.1 for additional discussion of leaching that should be considered when estimating mass discharge from the vadose zone to groundwater.

Changes in mass discharge over time, as well as changes in mass discharge with distance from a source, can be used to assess attenuation/retention (see Section 10.4.5; Newell et al. 2021). At sites where multiple sources are present, it could also be used to identify the relative contribution of different sources for prioritization purposes (see Section 10.4.5). Note that it may be challenging to estimate the relative mass flux contribution of different sources where low PFAS concentrations are present in porewater and groundwater. In addition, it is important to consider the potential for increases in dissolved mass flux of some PFAS due to biotransformation reactions, desorption between transects, and/or spatially varied infiltration.

10.4.5 Contributions from Different Sources

The potential impact to a site from multiple sources, particularly in proximity to urban or developed locations, needs to be accounted for when assessing site data or identifying data gaps. Each source then needs to be assessed in terms of its specific contributions, and their relative importance or magnitude. Although there are no naturally occurring background levels of PFAS, it may be important to gain an understanding of the Site-specific anthropogenic background (see the text box in Section 10.1.2) concentrations that may be present at a site, as these can have significant implications for site characterization, assessing exposures, evaluating ecological and human health risks, and establishing site action and cleanup levels. Most states have guidance on how to establish site-specific background concentrations for their regulated contaminants.

Tools available to quantify relevant contributions from different types of sources are discussed below.

10.4.5.1 Atmospheric Deposition

Certain PFAS may be present in ambient air and may be elevated near sources such as landfills, WWTPs, fire training facilities, and manufacturing plants (Section 2.6). Many PFAS exhibit relatively low volatility; however, airborne transport of some PFAS can be a relevant migration pathway for some industrial releases. Sections 5.3.2 and 6.1 provide an overview of transport of aerosols and particulates via air. To assess relative contributions from atmospheric sources, air sampling for PFAS can be conducted. Additionally, air dispersion models, such as AERMOD or Industrial Source Complex (ISC3) Model, can be employed to estimate airborne PFAS concentrations and total wet and dry deposition rates at designated receptor locations. Examples where AERMOD could be beneficial during site characterization activities include sites with no obvious source area and sites in industrial areas with multiple potential sources of airborne PFAS. See Section 2.6 for additional details on the most typical PFAS source scenarios.

10.4.5.2 Upgradient Site Contributions

PFAS persistence in the environment and their use in a multitude of industrial processes and commercial products result in potential for nonsite-related inputs, similar to other mobile contaminants (Figures 9-1, 9-2 and 9-3). Assessment of potential upgradient site inputs is recommended. The very low health advisory criteria for groundwater only increase the potential importance of identifying what might otherwise be considered "minor" upgradient sources and may result in alternate source identification (Sections 10.3.2 and 10.5). As part of site investigation of an air deposition release, soil data can be statistically compared to background samples, evaluated for vertical stratification, and assessed for spatial distribution relative to the potential source. Groundwater data from the site may be compared to data from other locations using cluster analysis (i.e., a data analysis technique that explores the naturally occurring groups within a data set, which are known as clusters) to assess whether there was evidence of other source terms, or if the site in question appeared to be the sole source.

Alternate Sources

Sources that may exist within, upgradient of, or near a site under investigation, that are distinct from the PFAS source being investigated.

10.4.6 Transformation Pathways and Rates

As discussed in Section 5.4, the transformation of precursors may result in increasing concentrations of PFAAs such as PFOS and PFOA along the flow path of a dissolved plume. Transformation reactions may occur due to aerobic biological or chemical oxidation. For example, McGuire et al. (2014) concluded that infusion of dissolved oxygen to bioremediate hydrocarbons downgradient of a former burn pit also likely caused the transformation of precursor compounds to PFAAs such as PFHxS. Some methods that may be used to assess the degree to which transformation is affecting PFAS plume extent and stability include:

- plotting concentration isopleths for precursors and various PFAAs, for example, McGuire et al. (2014)
- use of the total oxidizable precursor (TOP) assay to identify whether precursors are present that may be available for transformation to PFAAs at a point in the plume (Section 11.2.2)
- assessment of ratios of precursor and daughter product species at monitoring wells situated along the centerline of a plume, or the ratio of various PFAAs in various portions of a plume. For example, McGuire et al. (2014) plotted an isopleth map for the ratio of PFHxS to PFOS to show that in areas where dissolved oxygen was injected this ratio was as high as 50, and in other areas where bioremediation was not conducted this ratio was less than 1.
- use of concentration trends along a plume centerline and quantitative methods described in USEPA (1998) to estimate precursor transformation rates
- use of concentration trends along a plume centerline for precursors identified using high-resolution analytical techniques (see Section 11.2.2.5) to evaluate if transformation to presumptive intermediates and end products is occurring during plume transport (Nickerson et al. 2020)
- calculating the site-wide mass of precursors remaining vs. mass of PFAA end products (PFAAs) to estimate the time-averaged transformation rate since the time of release
- groundwater modeling to demonstrate that the relative plume lengths of different PFAAs with different retardation coefficients can be explained only through the transformation of precursors, for example, McGuire et al. (2014).
- a literature review to identify potential precursor transformation mechanisms and evaluate whether site geochemistry and redox conditions are favorable for the occurrence of these mechanisms.

Another method that may be used to illustrate the occurrence of these transformations is radial diagrams. See the case study in Section 15.1.1.

Figure 10-1 shows three radial diagrams based on data from an AFFF release site (McGuire et al. 2014). Each radial diagram compares groundwater concentrations at a monitoring well within the oxygen infusion zone to concentrations at a well approximately 76 m upgradient. The radial diagram shown at the left of Figure 10-1 compares concentrations for five PFCAs between these two wells; the middle diagram shows concentrations from the TOP assay conducted using samples from each well; and the radial diagram on the right compares concentrations for four PFSAs.

These radial diagrams illustrate that oxygen infusion into groundwater likely stimulated the production of mainly PFHxA, PFPeA, PFHxS, and PFBS. The middle radial diagram shows that the difference in TOP assay results between the upgradient well and the well in the oxygen infusion zone does not explain the large PFAAs concentration increases that were observed at the well in the oxygen infusion zone. The TOP assay results were low at both wells throughout the area. This suggests that desorption and subsequent transformation of precursors were occurring within the oxygen infusion zone. These radial diagrams are also useful for evaluating relative concentrations of various PFAAs at each monitoring well. The use of radial diagrams for additional types of trend analysis is discussed further in Section 10.4.9.4.

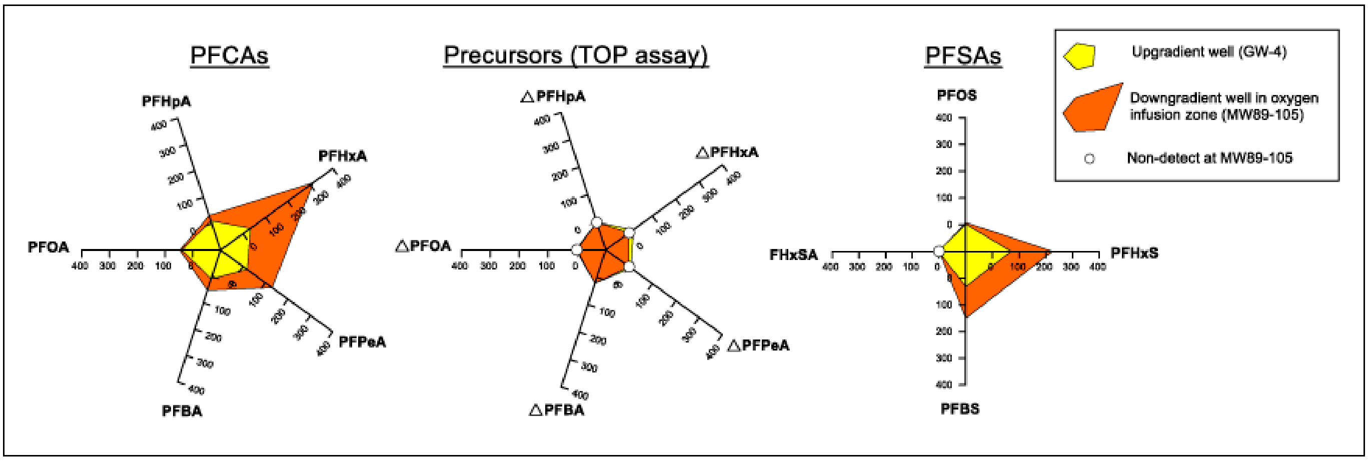


Figure 10-1. Radial diagrams showing the production of various PFAAs in the vicinity of an oxygen infusion zone at an AFFF release site remediated for hydrocarbons in groundwater*Source: G. Carey, Porewater Solutions. Used with permission.*

10.4.7 Assessing Retention, Migration, and Attenuation Processes

The degree to which PFAS are retained, migrate, and/or attenuate in site media has significant implications for site remediation and management. Migration of PFAS in groundwater is a primary concern at most sites, and the migration rates are influenced by the physical-chemical properties of individual PFAS, as well as different processes that act on PFAS during transport. Depending on site-specific conditions, several nondestructive processes can contribute to decreasing PFAS concentrations with respect to distance from the source area(s) or in the source area itself over time. Understanding these processes is critical for confirming that sufficient data have been collected to identify the relevant site-specific processes, establish migration rates, assess plume stability (see Section 10.4.8), model fate and transport (see Section 10.4.9), and ultimately inform further remedial decision-making (see Section 12). Table 10-1 summarizes the types of data that could be collected and analyzed to evaluate and quantify PFAS retention, migration, and attenuation processes at a site. This table summarizes information in previous subsections and is structured similarly to the methodology included in Newell et al. (2021) as the basis for evaluating natural attenuation as part of a site remediation and management strategy. However, it should be recognized that this process is also applicable to any setting where the information would improve the CSM and remedy evaluation process for PFAS. Lastly, it is essential to understand that individual PFAS have unique properties that affect their retention and attenuation. Therefore, an evaluation of site-specific retention and attenuation processes should consider variations between individual PFAS. For example, it may be possible that PFOS may be significantly retained at a site whereas PFNA may experience less retention and/or attenuation.

Table 10-1. Methods to Assess PFAS Retention, Migration, and Attenuation (adapted from Newell et al. (2021))

Topic	Investigative Method	Supporting Investigative Method

Evaluating whether sorption to solid-phase and/or air-water interface and matrix diffusion contribute to retention of PFAS	• Detailed sampling of soil and groundwater to establish distribution of PFAS mass between vadose zone vs. saturated zone, low permeability vs. high permeability soil zones, and sorbed vs. aqueous phase • Calculating the ratio of PFAS mass to PFAS mass discharge (high ratio implies higher retention) • Calculating the ratio of saturated zone PFAS mass to PFAS mass discharge (high ratio implies higher retention/attenuation)	• High-resolution stratigraphic data to facilitate estimation of matrix diffusion (for example, high percentage of low-permeability soils in groundwater-bearing unit is consistent with matrix diffusion effects • Collection of hydrogeologic and geochemical data such as organic carbon, anion and/or cation exchange capacity, salinity, moisture content, porosity, bulk density, and mineral content to evaluate their relationships with PFAS concentrations • Measurement and comparison of relative plume lengths for individual PFAS, PFAS subgroups, and/or PFAS chains
Evaluating transformation of precursor compounds and impact on migration	• Detailed sampling of soil and groundwater to establish distribution of PFAS between precursor forms vs. PFAAs throughout site • Evaluation of PFAA concentration and/or PFAAs as percent of total PFAS	• Estimation of bulk precursor attenuation rates using field data • Estimation of precursor attenuation rates using fate and transport modeling • Geochemical data showing where conditions are more supportive of degradation (aerobic) vs. less supportive of degradation, as well as influences of these conditions on observed trends (for example, where is majority of precursor mass: anaerobic or aerobic zones)
Quantifying influence of processes on PFAS migration/persistenc	• Evaluation of concentration trends with distance along plume centerline • Evaluation of mass discharge with distance along plume centerline • Evaluation of mass discharge from vadose zone to groundwater over time • Evaluation of source area concentration(s) over time • Evaluation of whether the plume footprint is stable or shrinking over time • Evaluation of the advancement rate of the plume footprint and whether downgradient zones have sufficient assimilative capacity zones	• Comparison of expected PFAS plume length in the absence of retention/attenuation (i.e., length if plume was advancing at the groundwater seepage velocity) to the observed PFAS plume length • Predictions of plume behavior over time using screening-level fate and transport models that include multiple PFAS retention processes • Predictions of plume behavior over time using more detailed 3-D contaminant transport models that incorporate additional flow data and other site-specific parameters

10.4.8 Assessing Plume Stability

At sites where PFAS has been detected in groundwater, it may be necessary to evaluate PFAS plume stability—whether the plume is stable, receding, or expanding. Plume stability and plume advancement rates are an important consideration for remedy selection. Many PFAS plumes are expected to be long-lived and possibly expanding due to the presumed lack of transformation of PFAAs and the mobility characteristics of many PFAS (especially those with shorter carbon chain lengths and anionic functional groups). Methods for evaluating plume stability include qualitative evaluations of temporal plume trends or statistical evaluations such as Mann-Kendall (ITRC 2013; ITRC 2016; AFCEC 2012; USEPA 2009).

Data uncertainties may have a greater than usual impact on plume stability evaluations for PFAS sites because of the low concentrations assessed. Monitoring records may be relatively limited, both in terms of the number of locations and the number of events that are available to evaluate. Biotransformation of precursors may also have an impact on plume stability evaluations. As such, more frequent or longer duration monitoring may be required to confirm trends or plume stability. A fate and transport model may also help provide predictions of plume behavior over time, and may be adjusted as additional site-specific data become available to aid calibration.

10.4.9 Modeling PFAS Fate and Transport

Some modeling of PFAS fate and transport has been conducted for vadose zone, groundwater, and atmospheric dispersion (McGuire et al. 2014; Barr 2017; Carey et al. 2019; Guo, Zeng, and Brusseau 2020; Persson and Andersson 2016; Gassmann, Weidemann, and Stahl 2021). Sima and Jaffe (2021) provided a critical review of applicable transport processes, modeling approaches, and potential limitations and uncertainty associated with modeling PFAS transport using existing approaches. Modeling the fate and transport of PFAS may have significant uncertainty contributed by precursor concentrations, transformation pathways and rates, and other factors. Because several of the key PFAS have not been shown to degrade naturally in the subsurface, other processes such as sorption, diffusion, and dispersion may be more important for understanding PFAS behavior upon release. However, many of these processes, such as desorption, are not well understood for PFAS (Sima and Jaffe 2021), and the accurate measurement or estimation of input parameters can be difficult. Although modeling of PFAS transport may be desirable and appropriate under certain conditions, the uncertainty of PFAS transport simulations requires that the results be qualified. Site-specific data are important for evaluating some potential model input parameters such as K_{oc}, which can exhibit significant spatial variation. This is particularly true in source zones, vadose zones, and at or near the water table. There are situations where modeling of PFAS transport may not be appropriate due to a lack of site-specific input parameters or reliable physical chemical properties for a particular PFAS.

10.4.9.1 Vadose Zone Modeling of PFAS Fate and Transport

There may be cases where an investigator wants to conduct a general screening-level evaluation of PFAS transport in the vadose zone under different scenarios. In such cases, the use of an existing vadose zone model may provide some benefit, but only if there is a thorough understanding of the inherent limitations of the model and if the uncertainty in the results is properly communicated.

Vadose zone models such as USEPA’s VLEACH (information and model available at https://www.epa.gov/water-research/vadose-zone-leaching-vleach), and Seview’s Seasonal Soil (SESOIL) compartment model (information and model available at http://www.seview.com/aboutsesoil.htm) can simulate one-dimensional vertical transport in the vadose zone via diffusion, adsorption, volatilization, biodegradation, cation exchange, and/or hydrolysis. Most PFAS are resistant to biotic or abiotic degradation, and in general PFAS are far less volatile than many other contaminants. With the exception of the few volatile PFAS such as the FTOHs (Section 4.2.5 and Table 4-1), the most important vadose zone processes to model are the physical transport processes. However, these models do not include air-water interfacial processes that appear to be important for vadose zone migration of PFAS. Other limiting factors for these models include that they simulate flow in only one dimension (vertical), and they may not adequately capture complex nonlinear or rate-limited sorption processes for PFAS. It is also important to note that these existing models have not been validated for use with PFAS. For these reasons, these models may not be appropriate for use with PFAS at this time.

The Michigan Department of Environment, Great Lakes, and Energy (EGLE) completed a review in 2020 that evaluated several vadose zone models (MI EGLE 2020) to simulate transport of PFOA and PFOS from municipal biosolid-amended soil through the unsaturated zone to the saturated zone. Models were initially screened and nine models were selected for critical review. From the nine models reviewed, HYDRUS, an unsaturated flow and transport model (information and model available at https://www.pc-progress.com/en/Default.aspx?hydrus), was recommended as the most suitable model for vadose zone modeling of PFOA and PFOS at the time of the EGLE review. (MI EGLE 2020).

Several research groups are attempting to develop models for PFAS transport in the vadose zone that more accurately represent some or all of the relevant processes. In some cases, these efforts involve modifying HYDRUS to incorporate these processes, while other groups are developing their own vadose zone models to do the same. Several studies discussing vadose zone modeling are presented below with a simplified, possibly more efficient model discussed in Guo et al. 2022.

Guo, Zeng, and Brusseau (2020) (referenced in Section 10.4.1 above) developed what they believed to be “the first mathematical model that accounts for surfactant-induced flow and solid-phase and air-water interfacial adsorption.” They applied the model to simulate PFOS transport in the vadose zone at a model fire-training area site impacted by AFFF. The simulations were useful in developing general concepts of PFAS retention as described in Section 10.4.1. In addition, and more generally, the mathematical model provides a quantitative framework that can be extended to examine the complex interactions between dynamic flow and adsorption processes at field sites (Guo, Zeng, and Brusseau (2020).

Zeng and Guo (2021) went on to develop a three-dimensional model for PFAS leaching in the vadose zone that allows for quantification of impacts from subsurface heterogeneities, which the authors concluded to be among the primary sources of uncertainty for predicting PFAS leaching and retention in the vadose zone.

"Due to significant computational cost and the requirement for detailed input parameters for the models," developed by Guo, Zeng, and Brusseau (2020) and Zeng and Guo (2021), Guo et al. (2022) developed a simplified model better suited for a screening tool to quantify vadose zone PFAS leaching. The derived analytical solutions incorporate multiple transport processes (with simplifying assumptions such as linear sorption) and allow for varied initial conditions. The solutions were "then validated by application to miscible-displacement experiments under a wide range of conditions and by comparisons to a state-of-the-art comprehensive model under both experimental and field conditions applicable to PFAS-contamination sites" (Guo et al. 2022). Based on these results, the authors concluded that "the simplified analytical model provides an efficient and accurate screening-type tool for quantifying long-term PFAS leaching in the vadose zone" (Guo et al. 2022).

Silva, Simunek, and McCray (2020) modified the one-dimensional and two-dimensional versions of HYDRUS "to simulate the effects of non-linear air-water interface (AWI) adsorption, solution surface tension-induced flow, and variable solution viscosity on the unsaturated transport of PFAS in the vadose zone." Available literature-derived unsaturated transport data for PFOA and PFOS were used to validate the revised models and provide example simulations. The study simulations showed that while AWI adsorption of PFAS can be a significant source of retention within the vadose zone, it is not always the dominant source of retention (Silva, Simunek, and McCray (2020). The contribution of solid-phase sorption can be considerable in many PFAS-contaminated vadose zones (Silva, Simunek, and McCray 2020). Further, the effects of soil textural heterogeneities on PFAS unsaturated transport are demonstrated in the example results.

A follow-up to a leaching study performed by Stahl et al. (2013) (referenced in Section 10.4.1) was completed by Gassmann, Weidemann, and Stahl (2021). The study used 8 years of data from a lysimeter and MACRO—a one-dimensional, process-oriented, dual-permeability model for water flow and reactive solute transport in soil (information and model available at https://www.slu.se/en/Collaborative-Centres-and-Projects/SLU-centre-for-pesticides-in-the-environment/models/macro-52/). The study evaluated the ability of MACRO to simulate leaching and plant uptake of PFOA and PFOS using two adsorption concepts: a kinetic two-side sorption concept usually applied for pesticide leaching (scenario I) and the formation of what Gassmann, Weidemann, and Stahl (2021) called non-extractable residues (NER) (scenario II). NER are adsorbed PFAS that either do not leach or leach very slowly from soil. Leaching of PFOA and PFOS could be adequately simulated for scenario II, but scenario I was not able to reproduce sampled leaching concentrations (Gassmann, Weidemann, and Stahl 2021). Plant uptake was simulated well in the first year after contamination but was not simulated well in the following years (Gassmann, Weidemann, and Stahl 2021). The model results suggest that more than 90% of the original mass of PFOA and PFOS is present as NER after 8 years, which the team concluded was a larger percentage of the mass compared with other studies (Gassmann, Weidemann and Stahl 2021). The authors also concluded that even though there are open questions that necessitate additional research, "the study showed that it is possible to use an existing leaching model for the long-term simulation of PFOA and PFOS leaching in unsaturated soils and the short-term simulation of plant uptake." Furthermore, they concluded that even though not all environmental processes are yet understood, this model may already provide valuable information for groundwater protection and crop safety.

10.4.9.2 Groundwater Modeling of PFAS Fate and Transport

The development and application of modeling approaches for PFAS in groundwater is relatively limited to date, likely reflecting the complexity of PFAS fate and transport processes, the range of chemical properties, and the uncertainty regarding appropriate parameter values to use in existing models. Several processes that are expected to influence PFAS fate and transport (see Section 5) pose challenges for modeling PFAS in groundwater, including:

- Nonlinear sorption. Linear sorption implies that the distribution of a compound between its dissolved phase and any solid phases that are present (for example, soil particles) is independent of the concentration of the compound itself. PFAS sorption has been shown to be concentration-dependent, such that models that account for this behavior are better suited for applications with wide concentration ranges. However, this adds complexity because it relies on an understanding of the appropriate PFAS sorption isotherm(s) and associated parameters for the site-specific application.
- Rate-limited sorption. Solute transport models typically rely on an initial assumption of equilibrium partitioning between dissolved and sorbed phases on a compound. However, several studies have demonstrated that PFAS sorption-desorption is a rate-limited process. This requires a more detailed approach in which both the dissolved and sorbed phases are modeled to incorporate mass transfer between the phases.
- Precursor transformation. PFAS are typically released as mixtures of different compounds, a portion of which may not be identifiable using current analytical approaches. Solute transport models that rely on simplified

> assumptions (for example, first-order kinetics, stepwise reaction pathways) may not be able to accurately capture in situ transformation patterns. Even for PFAS transformation pathways that have been identified as potentially relevant using lab or field data, there is little understanding of in situ rates to use for modeling purposes.

Despite the challenges groundwater modeling is being attempted for some situations. Some groundwater modeling studies from the literature are discussed.

Pietrzak (2021) completed a review of available software for modeling organic pollutants in groundwater. One example, simulated transport using MODFLOW/MT3DMS (Shin et al. 2011), which summarized simulation of PFOA transport in several media, including groundwater, from a manufacturing source and linking the models. Shin et al. (2011) concluded that their models may be useful for estimating past and future concentration of PFOA in water wells in the study area. However, the effort did not include all processes that are now recognized as relevant for PFAS fate and transport.

Groundwater modeling studies published to date have focused on the impacts of specific processes and/or remediation on PFAS plume development. For example, Gefell et al. (2022) modeled hypothetical PFOA groundwater plumes using MODFLOW and MT3D based on purely hypothetical remediation and data. The study evaluated the differences between a plume resulting from a PFOA-only source compared to a source with precursors located in the overlying vadose zone. Because the plumes from both scenarios exhibited relatively similar concentrations and lengths in the absence of remediation, the authors concluded that source zone characterization is particularly important when predicting long-term plume behavior and that it may be appropriate to calibrate a model to both a terminal PFAA-only source plume and one from a precursor source. After remediation of the source and an extended postremediation flushing period, the scenario with a precursor-based source resulted in a longer plume with higher concentrations. The results for this scenario were sensitive to the precursor degradation rate, and the authors used literature values in their simulations that were derived from a combination of lab-based and field-based data.

As another consideration to improve modeling transport of PFAS in groundwater, the REMChlor-MD model (Farhat et al. 2018) has been proposed for evaluating the possible effects of matrix diffusion processes on PFAS distribution (Newell et al. 2021). This includes a study by Kulkarni et al. (2022) in which this screening-level model was used to estimate the impact of matrix diffusion on the PFOS plume extent using field data from a well-characterized AFFF site where significant PFAS mass was known to be present in lower permeability soils. The model predictions suggested that matrix diffusion contributed to a PFOS plume length at this site that was approximately 40% of the length that would have been observed in the absence of matrix diffusion. The study predicted that matrix diffusion was reducing the plume advancement rate, and that source remediation would have limited impact on the rate of future plume advancement. Another study used REMChlor-MD modeling to examine the types of sites where matrix diffusion processes would be most relevant, and the authors concluded that aquifers with embedded lower permeability layers and lenses exhibited shorter PFOS plumes than aquifers with underlying and/or overlying aquitards (Farhat et al. 2022). Long time frames were needed for plume stabilization, but these predictions were highly sensitive to dispersion parameter values since PFOS was assumed to not degrade over time. These results emphasize the site-specific nature of various PFAS fate and transport processes and highlight the importance of site-specific assessments.

In addition, selecting a representative source term for modeling may be difficult due to a lack of available data and/or limitations in the model for handling potentially complex source behavior. Ideally, groundwater transport models for PFAS should incorporate data from vadose zone models and air deposition models to provide a more holistic representation of the source term. As mentioned above, this linked approach was used in a 2011 study that examined regional transport of PFOA from a manufacturing source (Shin et al. 2011), but the model did not include all processes that are now recognized as relevant for PFAS fate and transport. In other cases, groundwater transport modeling with discharge to surface water was used to evaluate PFAS distribution within watersheds or regional scales (Raschke et al. 2022), though the level of complexity of such integrated modeling approaches may be high and could introduce additional uncertainty, particularly if the data available to calibrate the models are limited.

Another use of groundwater modeling is to evaluate groundwater surface interactions. Divine et al. 2023 provided a brief discussion of the current state of modeling PFAS and concluded that current models lack do not include complexities such as mass transfer rate limitations and precursor transformation. Additional model development and verification is needed.

10.4.9.3 Air Modeling of PFAS Fate and Transport

Modeling PFAS transport in air is receiving more attention, and USEPA has recently developed an air quality model named the Community Multiscale Air Quality model (CMAQ) for these purposes (USEPA 2022). From a personal communication with James A. Thurman, Ph.D., USEPA/OAQPS/AQAD, Air Quality Modeling Group, CMAQ can handle any kind of atmospheric reactions PFAS would undergo during transport and would also include long-range transport, more than 50 km from the source of PFAS. As more information is learned about PFAS, CMAQ can be updated to include the atmospheric reactions for PFAS. See D'Ambro (2021) for an example of the use of CMAQ to evaluate a mixture of PFAS from a fluoropolymer manufacturing facility.

Another example of atmospheric modeling of PFAS was performed by Moreno (2019). Moreno (2019) modeled transport of PFOA and HFPO-DA from two manufacturing facilities using CALPUFF, a non-steady state, long-range transport model. In addition, air quality models such as AERMOD or IISC3 Model are identified in Section 10.4.5.1. An example use of AERMOD can be found in Barr 2017. AERMOD was used to simulate the emission of PFOA from stacks at former manufacturing facilities in Bennington, Vermont, and the resulting air dispersion and deposition. The facilities applied PFTE to some fiberglass fabrics.

AERMOD is applicable in the near field, less than 50 km from the source of PFAS for qualitative assessment of local deposition from a source of PFAS when atmospheric reactions are not necessarily important (From a personal communication with James A. Thurman, Ph.D., USEPA/OAQPS/AQAD, Air Quality Modeling Group). AERMOD deposition fields could be used to analyze the spatial distribution of deposition near the source and identify areas of interest to consider for further study. More information for AERMOD can be found in USEPA (1995); Wesley, Doskey, and Shannon (2002); and USEPA (2003).

USEPA provides a Support Center for Regulatory Atmospheric Modeling (SCRAM) website at https://www.epa.gov/scram (accessed August 10, 2023) that includes links to air quality models and tools.

10.4.9.4 Visualization Methods

One of the challenges associated with characterization of PFAS sites is the analysis of trends for a number of PFAS constituents that may be sampled in soil and groundwater, and then the communication of the results of these analyses to a less technical audience. Typical site characterization visualization methods such as plume maps, cross-sections, fence diagrams, 3D models may be used to depict the horizontal and vertical extent of PFAS plumes. Several other visualization methods may be helpful when analyzing PFAS data, including:

- bar charts that show the relative concentrations of individual PFAS constituents at each location to help evaluate PFAS composition trends in soil and groundwater (for example, figures 6 and 7 of 7 Field (2017), Figure 15-1)
- radial diagrams to illustrate:
    - transformations of precursors to PFCAs and/or PFSAs along a flow path (for example, see Section 15.1.1)
    - relative concentrations of constituents at each sample location to assist with source fingerprinting and to identify potential risk drivers in different parts of a plume
    - locations of potential hot spots
    - general extent of a PFAS plume.

Case study examples of these different methods are discussed in Section 15.1.

10.5 Forensics and Source Identification

The field of environmental forensics is a formal technical discipline that spans chemistry, environmental science, and engineering (for example, Morrison 2000; Morrison and Murphy 2006; Mudge 2008; Murphy and Morrison 2015[]; Sullivan et al. 2001; Wang and Stout 2007). Environmental forensics is used to address problems such as source identification, timing of releases, and contaminant fate and transport. As compared to legacy contaminants such as PAHs and PCBs, the application of forensics to PFAS forensics is in its nascent stages. Researchers are still conducting studies to more fully understand the fate and transport of PFAS in the environment, and they continue to evaluate tools to investigate changes in PFAS composition for the purposes of source attribution. Multivariate methods have been applied to investigate sources of PFAS, including human exposure in the Faroe Islands (Hu et al. 2018), contributions to surface water in the northeast United States (Zhang et al. 2016), and contributions to surface water and sediment in South China (Pan et al. 2014). Benotti et al. (2020) and Charbonnet et al. (2021) both advocated the use of a variety of tools that are applied in a tiered approach for characterizing the PFAS signatures associated with source materials and environmental contamination. It has been observed that the PFAS sources profiles associated with different PFAS uses are frequently highly variable. Until a more complete understanding of the chemical composition of source materials is available, and until researchers understand the full scope of forensic information that may help elucidate sources, source libraries associated with different usage profiles are incomplete at best. Given these uncertainties, the best approach for associating or dissociating environmental contamination from one or more sources is to compare PFAS information in environmental samples to similar information from site-specific source areas. An overview of PFAS source identification analyses can be found in Dorrance, Kellogg, and Love (2017).

To that end, any site-specific investigation begins with a careful review of available records. In a best-case scenario, such records may directly link a source to environmental contamination without significant contribution from any other potential sources. More often than not, source attribution of PFAS contamination is more complicated. Groundwater plumes of PFAS contamination can be heterogeneous due to weathering and differential rates of subsurface transport between PFAS. Care must be taken not to attribute changes associated with fate and transport to different sources. Recent experience shows that multiple groundwater plumes with a similar or disparate profiles are commonly observed to intersect and commingle. If there are two or more likely sources contributing to mixed contaminant plumes, defining the footprint associated with these different sources can be challenging. In addition, atmospheric transport and deposition of PFAS can be important and result in PFAS sources with regional impacts (Ahrens et al. 2016; Davis et al. 2007; Galloway et al. 2020).

When identifying PFAS sources, some important factors to consider include:

- *data quality*, where care must be taken to ensure that analytical results from different time periods, different methods, or different labs are comparable, as older data sets may provide incomplete information when compared to more recent data
- *target PFAS list*, where a reduced compound list may prevent full differentiation between sources. Linear versus branched (isomer) distinction may also be important in differentiating sources
- *matrix effects*, care must be taken to account for differences in PFAS profiles associated with different matrices. For example, soil PFAS profiles can be significantly altered during leaching to groundwater
- *temporal effect*, where an understanding of historical production, use, and release of PFAS becomes important, as is an understanding of differences between samples due to weathering processes that may be interpreted as different sources
- *spatial effect* of long-distance air deposition and regional sources versus local sources
- *sample collection procedures* to ensure there is no cross-contamination from other sources during sampling
- *rigorous exploration of potential sources* to ensure that all sources of potential interest have been identified and considered
- *weight of evidence* based on multiple lines of inquiry

The following sections describe some of the source identification tools that may be used or considered for use in identifying sources of PFAS.

10.5.1 Source Identification Tools

Chemical fingerprinting often involves the evaluation of the relative proportions of different substances in a mixture to link contaminants in the environment to one or more known or suspected sources (see the text box in Section 10.4.5.2). The data from available analytical methods can be evaluated using various graphical, statistical, and geospatial techniques. These methods have been commonly used for legacy contaminants such as petroleum and chlorinated compound source identification and can potentially be applied to PFAS mixtures. The following sections describe some of the forensic information that may be useful to evaluate sources, as well as some tools for comparing samples within a data set.

10.5.1.1 Manufacturing Signatures

PFAAs (PFCAs and PFSAs) can be produced as a mixture of homologues of different chain lengths depending on the various manufacturing process(es) used (Section 2.2). PFAAs produced by electrochemical fluorination (ECF) can include both even and odd chain-length homologues. PFAAs produced by fluorotelomerization contain mostly even chain-length homologues. However, transformation of some of the fluorotelomer precursors results in the formation of odd chain length PFCAs (Prevedouros et al. 2006; Dasu, Liu, and Lee 2012; Liu and Mejia Avendano 2013). Most commercial laboratories can report PFCA homologues ranging from C4 to C14 and select PFSA homologues between C4 and C12. USEPA (2009) published PFCA profiles in various commercial products that showed different patterns of PFCA chain lengths. So, while chemical

fingerprinting for source identification may be useful for PFAS sites, changes in raw materials and processes over time, as well as environmental fractionation, must be taken into account.
Laboratories generally report the concentration of a given PFAA as the total of the branched and linear forms; however, the concentration of the linear form and an estimated concentration for the branched form can often be reported independently. The concentration of branched forms typically must be estimated because standards do not yet exist for most branched-chain PFAA (Section 11.2.1). Benskin (2011) used the absence of branched PFCA isomers in dated sediment cores of two lakes to support the conclusion that oxidation of FTOH was the major atmospheric source of PFCAs in the lakes and not direct transport of PFOA. Fredriksson (2016) used isomer profiles along with homologue patterns to assess the sources of PFAS in avian eggs. However, the potential for environmental fractionation must be taken into account when evaluating isomer profiles because linear and branched-chain isomers have different physical and biological properties, adsorption, and bioaccumulation (Fredriksson 2016; Miralles-Marco and Harrad 2015). Other examples of isomer analysis for PFAS source identification include Shi et al. (2015), Benskin, DeSilva, and Martin (2010), and Karrman et al. (2011).

Chiral fingerprinting through enantiospecific isomer differentiation is a potential method for source identification, although its use is still under development. Asher et al. (2012) applied this method to identify PFAS sources to an aquatic foodweb. However, they noted several limitations and assumptions when using this method for PFAS source identification.

10.5.1.2 High-Resolution Mass Spectrometry (HRMS)

High-resolution mass spectroscopic methods using quadrupole time-of-flight mass spectrometry (qTOF/MS) can be used to determine both the chemical formula and structure of unknown PFAS in source materials (see Section 11.2.2.5 for further information on qTOF/MS) (Newton et al. 2017; Moschet et al. 2017; Barzen-Hanson et al. 2017; Battelle 2020; Washington et al. 2020; Getzinger, Higgins, and Ferguson 2021; Guelfo et al. 2021). PFAS suspect screening libraries have been developed to include broader lists of PFAS analytes found across many different PFAS sources (Newton et al. 2017; Moschet et al. 2017; Barzen-Hanson et al. 2017; Getzinger, Higgins, and Ferguson 2021). Because analytical standards are not available for most PFAS included under this extended list of analytes, often these analytical tools are used for qualitative/semiqualitative analysis. These methods have the potential to greatly increase the number of identified PFAS, including precursors and the transformation products, and hence provide more accurate source identification (Washington et al. 2020, Getzinger, Higgins, and Ferguson et al. 2021; Guelfo et al. 2021). The addition of a broader list of analytes increases the power to resolve differences in PFAS profiles and therefore characterize sources and source footprints.

10.5.1.3 Visual Representations of Data

It is common to show representations of measured PFAS in figures or graphs to give the reader a visual sense for relative abundance. Two common graphs for representing PFAS data are bar graphs and radar plots. If one is considering the role of concentration, then it may be helpful to plot PFAS concentrations on the axes. However, if one is considering the patterns of data, then it is helpful to plot relative abundance, or the concentration of each PFAS divided by the sum of all measured PFAS, on the axes. It is also suggested to group subclasses of PFAS together and order them by perfluorinated alkyl chain length. For example, PFCAs ordered from the shortest to longest perfluorinated alkyl chain length, followed by PFSAs ordered from the shortest to longest perfluorinated alkyl chain length, followed by fluorotelomer sulfonates ordered from the shortest to longest perfluorinated alkyl chain length allows the viewer to compare changes in compositional patterns both within and between different subclasses of PFAS to assess changes that may occur due to environmental fate and transport. When showing data in this fashion, it is common to report estimated concentrations or J-flagged values and use the value of zero (0) for nondetects. However, other methods for assessing nondetects could be considered (Johnson et al. 2015). A comparison of PFAS signatures between two samples (Sample A and Sample B) using either bar graphs (Figure 10-2) or radar plots (Figure 10-3) is shown below.

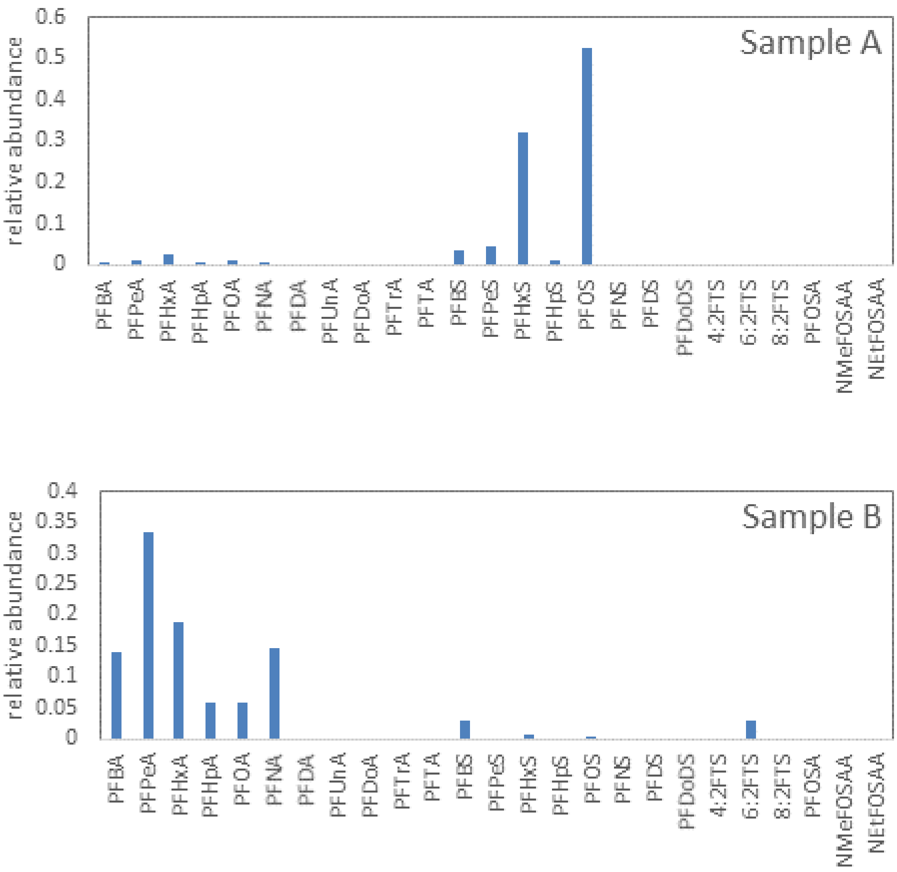


Figure 10-2. Comparison of PFAS signatures in Sample A and B using bar graphs. The concentration of each PFAS has been divided by the sum of all measured PFAS to represent the relative abundance of PFAS in each sample.

Source: M. Benotti, NewFields. Used with permission.

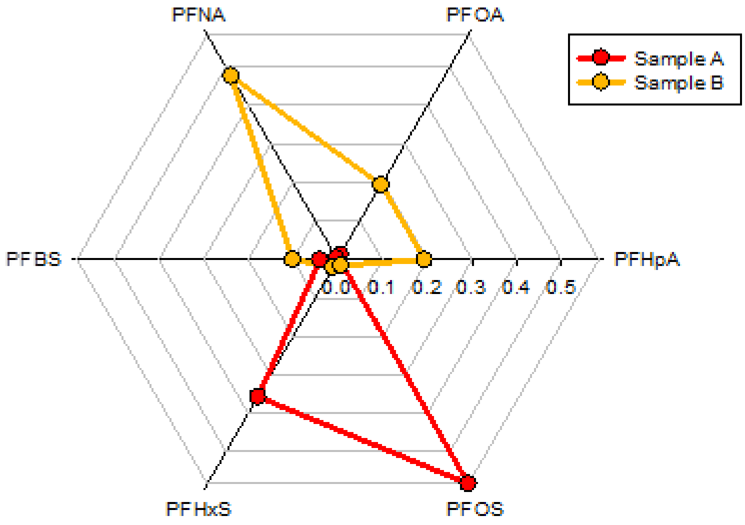


Figure 10-3. Comparison of PFAS signatures in Sample A and B using radar plots. The concentration of each PFAS has been divided by the sum of all measured PFAS to represent the relative abundance of PFAS in each sample.

Source: M. Benotti, NewFields. Used with permission.

10.5.1.4 Diagnostic Ratios

In some applications of PFAS forensics, it may be beneficial to show similarities or differences between sample signatures using relative abundances of one or more PFAS or diagnostic ratios, or double ratio plots. Without a comprehensive library of PFAS source materials, such ratios should be site-specific, and should be selected to query the data for a site-specific question and to show similarity or differences between contamination throughout the site and those in known or purported source area/s. Examples of factors that may help identify suitable diagnostic ratios include the relative abundance of PFCAs, PFSAs, or FTSs, the ratio of PFCAs to PFSAs (or more specifically the ratio of PFOA to PFOS), the ratio of even-numbered to odd-numbered PFCAs, the relative abundance of linear to branched isomers of selected PFAS, and others. Table 10-2 shows some example diagnostic ratios for PFAS in Sample A and Sample B above.

Table 10-2. Example diagnostic ratios to compare PFAS signatures of Sample A and Sample B.

	Sample A	**Sample B**
relative abundance of PFCAs	0.062	0.93
relative abundance of PFSAs	0.94	0.041
relative abundance of FTSs	0	0.029
PFCAs/PFSAs	0.066	22
PFOA/PFOS	0.0217	13

10.5.1.5 Multivariate Statistical Tools

The statistical methods used in fingerprinting chemical mixtures range from simple visual comparisons of the relative chemical composition in environmental samples to more sophisticated multivariate statistical analyses of large environmental data sets (Bock et al. 2021; Cejas and Barrick 2021; Wenning and Erickson 1994; Johnson et al. 2006; Otto 2016; Brereton 2009). Multivariate statistical tools are ideally suited to the analysis of chemical mixtures. These tools have been applied to chemical mixtures such as PCBs, hydrocarbons, and dioxins for many decades. PFAS data sets, including TOP assay data, are similarly amenable to a variety of multivariate numerical data analysis techniques that provide a means to categorize PFAS compositional data. The advantages of multivariate numerical methods are that they provide a convenient means to analyze large data sets and reduce the output into relatively straightforward graphical output that describes the most important factors affecting chemical variability throughout the data set. Principal component analysis (PCA) is a multivariate statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. In other words, it identifies and graphically shows the most important features of data that describe similarities and differences between sample chemistries within a data set. The investigator can use this tool to identify samples that have similar or different PFAS signatures and what changes are driving those differences. Changes in PFAS patterns may be attributable to changes associated with fate and transport, or there may be changes that can be explained only by additional sources. Figure 10-4 presents an example PCA scores plot, which demonstrates the similarity or dissimilarly of PFAS signatures between all samples in a data set. PCA is most effective when supplemented with other lines of evidence such as cluster analysis, ratios, and geospatial methods.

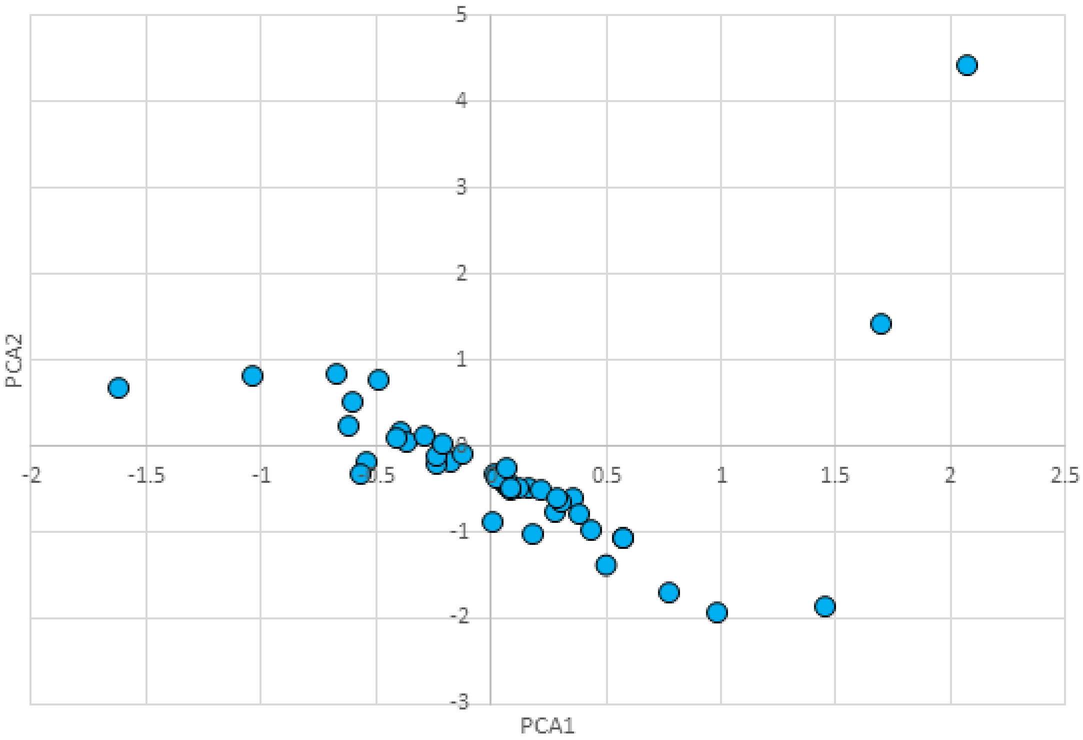


Figure 10-4. PCA scores plot of the analysis of a PFAS data set. Each circle represents the pattern of PFAS contamination of an individual sample. Samples that plot close together have similar PFAS signatures. Samples that plot apart have dissimilar PFAS signatures.

Source: M. Benotti, NewFields. Used with permission.

Examples of chemical fingerprinting for PFAS source identification can be found for wastewater treatment plants (Clara et al. 2008), differentiating AFFF sources (KEMI 2015; Hatton, Holton, and DiGuiseppi 2018; see also Section 3.5), landfills (Lang et al. 2017; Xiao et al. 2012), surface water (Xie et al. 2013), sediment (Qi et al. 2016), and groundwater (Yao et al. 2014). Multivariate statistical analyses (that is, PCA, cluster analysis, and unmixing models) and geospatial analysis have been used extensively to distinguish PFAS sources. Guelfo (2017) emphasized the importance of geospatial distribution of PFAS for source identification. Qi et al. (2016) used PCA–multiple linear regression, positive matrix factorization, and unmix models to identify four PFAS sources (textile treatment, fluoropolymer processing aid/fluororesin coating, textile treatment/metal plating, and precious metals). Zhang et al. (2016) used PCA, hierarchical clustering, and geospatial analysis to determine sources in the northeast United States, and Lu et al. (2017)[652] used factor analysis to classify three categories of PFAS in impacted groundwater. Pan et al. (2014) used PCA in water and sediment samples to distinguish between rural/agricultural and urban/industrial sources.

Other methods that have been applied to other chemical mixtures, such as statistical unmixing and big data/machine learning methods, also hold promise for the analysis of PFAS mixtures. As with any complex data analysis method, these methods have strengths and weaknesses that must be understood by the user. Thus, PFAS forensics practitioners must keep current on new developments in chemical forensics and statistical analysis. Given differences in the environmental fate and transport of different types of chemical mixtures and the complex behavior of PFAS, the forensics scientist must carefully evaluate any data analysis method to ensure it is being applied and interpreted appropriately. Because of the many complexities associated with PFAS production, historical usage, and fate and transport processes, the risk of incorrect conclusions can be especially high. We advocate for a weight of evidence approach based on (1) historical information regarding usage and other information, (2) a detailed consideration of transport pathways such as air emissions, spills, and wastewater discharge, (3) an analysis of transport processes such as local groundwater transport, the presence of groundwater divides and other barriers, and air speed and direction, (4) concentration gradients, (5) the analysis of diagnostic ratios, (6) multivariate statistical methods, (7) a consideration of branched versus linear isomers, and (8) other information that can be used to understand sources, discharges, and fate and transport.

SERDP PFAS Novel Methods for PFAS Source Tracking and Allocations

ER20–1375 Comprehensive Forensic Approach for Source Allocation of Poly- and Perfluoroalkyl Substances – Chris Higgins, Colorado School of Mines

ER20–1121 Establishing an Approach to PFAS Forensics and a PFAS Source Materials Forensic Library – Mark Benotti, NewFields Government Services

ER20–1205 Machine Learning Pattern Recognition for Forensic Analysis of Detected Per- and Polyfluoroalkyl Substances in Environmental Samples – Tohren Kibbey, University of Oklahoma

ER20–1265 Ultrahigh-Resolution Fourier-Transform Ion Cyclotron Resonance Mass Spectrometry for Fingerprinting, Source Tracking, and Allocation of Per- and Polyfluoroalkyl Substances (PFAS) – Jens Blotevogel, Colorado State University

ER20–1056 Improving Access and Utility of Analytical Data for the Confident Discovery, Identification, and Source-Attribution of PFAS in Environmental Matrices – Benjamin Place, NIST, Department of Commerce

Updated September 2023.

11 Sampling and Analysis

The PFAS Team developed a Sampling and Analysis training video with content related to this section.

Due to the extensive use of a wide array of PFAS resulting in trace levels of PFAS in most environmental media across the globe and the low parts–per–trillion screening and action levels, all aspects of a sampling and analysis protocol require a heightened level of rigor to avoid cross-contamination and achieve the level of accuracy and precision required to support defensible project decisions. This section focuses on providing the user with the appropriate tools and information to develop a site-specific sampling and analysis program to satisfy the project data quality objectives (DQOs).
Accurate and representative data support the development of a defensible conceptual site model (CSM), and ultimately the final remedy.

Section Number	**Topic**
11.1	Sampling
11.2	Analytical Methods and Techniques
11.3	Data Evaluation
11.4	Source Identification

Information on sample collection for PFAS is sparse, with only a handful of guidance documents available for a practitioner to reference. However, there are two peer-reviewed studies (Denly et al. 2019; Rodowa et al. 2020) on the potential for cross-contamination from commonly used sampling materials. These studies indicate that the potential for cross-contamination from the equipment used or possession of items that could potentially contain PFAS (for example, bug spray, food wrappers, and sunscreen) is extremely low and difficult to document. Most current guidance documents default to a conservative approach due to a lack of information at the time of publication. Although the actual methods of sample collection are similar to those used for other chemicals, there are several considerations for the practitioner when establishing a sampling program for PFAS. These include selection of proper personal protective equipment (PPE), documentation of protocols for sample handling and decontamination procedures, use of nonbiasing material (for example, tubing, sample bottles, pumps) that will or could reasonably come into contact with the sample media, and implementation of quality control (QC) protocols to meet project DQOs, among other considerations. This section will give practitioners the tools needed to prepare a sampling program that adequately addresses project-specific DQOs and limits, to the extent practicable, potential cross-contamination and sources of potential bias.

Analytical methods are still evolving for PFAS analysis, with several in development (USEPA 2021). Although some draft methods have been published (PFAS Analytical Methods provided as an Excel spreadsheet), not all are discussed in this document because details included in these methods are subject to change prior to the methods being finalized.

In the case of USEPA Draft Method 1633, an exception has been made in this document due to the USEPA Office of Water’s recommendation of its use in Clean Water Act (CWA) compliance testing applications, including National Pollutant Discharge Elimination System (NPDES), as well as the DOD’s requirement for the use of Draft Method 1633 for media other than drinking water (USDOD 2021). The publication of this draft method followed the completion of a single-laboratory validation of the method. The method is currently undergoing multilaboratory validation. The multilaboratory validation has been completed for aqueous matrices (wastewater, surface water, and groundwater) and QC criteria based on the results of this study have been incorporated into the current version of the method (Draft 4) (USEPA 2023). While the method remains identified as a draft method due to the ongoing validation efforts with respect to other matrix types (soils, sediment, biosolids, tissue, and landfill leachate), it is considered finalized for aqueous matrices (wastewater, surface water, and groundwater). Upon completion of the multilaboratory validation study for these matrices, the method will be revised once again and finalized for all applicable matrices and be proposed at 40 CFR Part 136 for nationwide Clean Water Act monitoring. This method is applicable to wastewater, groundwater, surface water, landfill leachates, soil, sediment, biosolids, and tissue.

The USEPA Office of Land and Emergency Management has validated and published sample preparation procedure and analysis procedures applicable to groundwater, surface water, and wastewater. USEPA SW-846 Method 3512 is a sample preparation method, and USEPA SW-846 Method 8327 is the associated analytical method.

Currently, three USEPA methods are validated and published for the analysis of PFAS in drinking water: USEPA Method 537 (USEPA 2009), USEPA Method 537.1, Version 2.0 (USEPA 2020), and USEPA Method 533 (USEPA 2019). For simplicity in the text, subsequent references to USEPA Method 537.1 assume the most current version. These methods are required for PFAS analyses of drinking water and include performance data for drinking water from surface water and groundwater sources. These methods are prescriptive in that changes to preservation (including sample collection, in the case of USEPA Method 537.1), sample extraction steps, and quality control requirements are prohibited by both methods.

The DOD has also validated and published a method (DOD AFFF01) for the determination of PFOA and PFOS in AFFF concentrates for demonstration of compliance to MIL-PRF-24385 (Willey 2021).

This section will be updated as new information on sampling considerations and analytical methods/procedures becomes available.

11.1 Sampling

11.1.1 General

Sampling conducted to determine PFAS concentrations in drinking water, other aqueous media, soil, sediment, air, biota, and other media is similar to that for other chemical compounds, but with several additional specific considerations and protocols. Typical guidance and procedures, such as ASTM International D 4823-95 and D 4448-01, USEPA compendium EPA 540/P-87/001a, OSWER 9355.0-14, USEPA SESDPROC-513-R2, and USEPA SESDPROC-305-R3, remain the basis for a PFAS sampling protocol. Because of the need for very low laboratory quantitation limits and the widespread use of PFAS in common materials, field and equipment blanks are needed in greater amount and frequency than in other analyses. In addition, special consideration may be needed to address the potential for background sources of PFAS in the environment, sample cleanup criteria, and the potential need for modified decontamination measures.

Examples of USEPA region-specific or program-specific PFAS sampling protocols include:

- USEPA (2019) Region 4, Laboratory Services and Applied Science Division, Athens, GA, *Field Equipment Cleaning and Decontamination at the FEC*, ASBPROC-206-R4, 2019
- DOD AFFF01 *Determination of Perfluorooctanoic acid and Perfluorooctanesulfonic acid in Aqueous Film Forming Foam (AFFF) for Demonstration of Compliance to MIL-PRF-24385* (Willey 2021)
- State guidance:
    - MA DEP (2022) Massachusetts Department of Environmental Protection, *Interim Guidance on Sampling and Analysis for PFAS at Disposal Sites Regulated under the Massachusetts Contingency Plan*.
    - Washington Department of Ecology (2017) *Quality Assurance Project Plan; Statewide Survey of Per- and Poly-fluoroalkyl Substances in Washington State Rivers and Lakes.*
    - NH DES (2022) New Hampshire Department of Environmental Services, *Laboratory Testing Guidelines for Per- and Polyfluoroalkyl Substances (PFAS) at Waste Sites,*
    - MPCA 2022 Minnesota Pollution Control Agency, *Guidance for Per- and Polyfluoroalkyl Substances (PFAS): Sampling*
    - Michigan Department of Environment, Great Lakes, and Energy (EGLE) 2018 to present, PFAS Sampling Guidance Documents, including:
        - MI EGLE (2021) PFAS Sampling Guidance
        - MI EGLE (2019) Surface Water Foam PFAS Sampling Guidance
        - MI DEQ (2018) Wastewater PFAS Sampling Guidance
        - MI DEQ (2018) Surface Water PFAS Sampling Guidance
        - MI DEQ (2019) Fish Tissue Sampling Guidance

The list provided above is not comprehensive; project teams should consider state-specific and USEPA guidance as available.

A work plan (that is, a quality assurance project plan (QAPP)) should be implemented to address PFAS-specific considerations. If a work plan is not created for a project, the sampling and quality control (QC) elements outlined in Section 11.1.6 should be implemented. If regulatory procedures, methods, or guidelines are inconsistent with the needs of a PFAS sampling program, such as requiring the use of fluoropolymer tubing, the governing agency should be contacted directly to determine if an exception can be made or an alternate approach is needed. A CSM (if available, see Section 10.2) should be evaluated to support development of the project-specific DQOs as part of the work plan. The review should include information on previous site uses, PFAS use/manufacturing/handling practices, other possible contaminants and their uses, and/or related remediation activities and historical PFAS data, to determine all possible source areas of PFAS. Previous or ongoing remediation of other contaminants of concern can add a layer of complexity to a site's geochemistry and the fate and transport of PFAS.

Although some sampling elements (for example, sample bottle, preservation, and holding times) are defined by USEPA Methods 537.1, 533, 1633, and 8327, these methods do not provide all the information that is needed to conduct a sampling event for PFAS. However, DOD AFFF01 contains all the information needed to conduct sampling of AFFF concentrates. Tables 11-2 and 11-5 are included in the PFAS Analytical Methods Excel File, and cover the sample container types, sample size, number of containers required, and holding time and preservation requirements for each of these published PFAS analytical methods, respectively.

Communication with the laboratory before, during, and after sampling is conducted, is critical in ensuring that project needs are met. If a sample is from an area known or suspected to be highly contaminated with PFAS, it is important that this is communicated to the laboratory. The chain-of-custody form should indicate samples that potentially contain a high concentration of PFAS. As stated in USEPA Draft Method 1633 (USEPA 2023), laboratories should prescreen all samples to select the necessary sample preparation procedures and to avoid contamination of their laboratory equipment and contamination of other field samples.

Any water used for field QC blanks (for example, field and decontamination blanks) should be supplied by the laboratory performing the analysis. The laboratory should provide documentation verifying that the supplied water is PFAS-free. "PFAS-free" is the project-defined concentration that associated blank concentrations must be below (examples: less than the detection limit; less than half the limit of quantitation (LOQ)) to ensure an unacceptable bias is not introduced into the sampling and analysis processes and project data quality objectives can be met. The work plan should clearly state the project's definition of "PFAS-free." Review of the laboratory's standard definition of "PFAS-free" upfront is necessary to ensure that it meets project needs and is a critical step in laboratory selection for a project. Laboratories verify the PFAS content of each batch of supplied water through analysis. Documentation of this verification should be maintained for data validation purposes and should be reviewed by the project team to ensure that the project's definition of "PFAS-free" is met. If the water was not supplied by the laboratory, a sample of the water used in the field should be sent to the laboratory for testing.

11.1.2 Equipment and Supplies

Many materials used in environmental sampling can potentially contain PFAS. There is limited published research or guidance on how certain materials used by field staff or in sampling equipment affect sample results (see Denly et al. 2019; Field et al. 2021, Assessing the Potential for Bias in PFAS Concentrations during Groundwater and Surface Water Sampling, SERDP Project ER19-1205; Rodowa et al. 2020). However, a conservative approach is recommended to exclude materials known to contain the PFAS that are the target of the analysis from a sampling regimen, and such an approach should be documented accordingly in the work plan. Obtain and review all Safety Data Sheets (SDSs) before considering materials for use during PFAS sampling, as product manufacturing formulations can change over time. If PFAS or the terms "fluoro" or "halo" are listed on the SDS, it is recommended that piece of equipment/supply not be used. Exclusion from the SDS does not necessarily mean the equipment/supply is not contaminated with PFAS. PFAS could have been used not as a component of the equipment/supply, but as a material used in the manufacturing process itself (for example, mist suppressant or mold coating). This can result in the equipment/supply manufactured containing PFAS. If necessary, materials in question can be sampled and analyzed for PFAS, or thorough decontamination and collection of equipment blanks can provide sufficient quality assurances. Ultimately, a sampling program should produce defensible data, and the best way to protect the integrity of samples is to ensure they are not compromised by contaminants originating from sampling equipment or otherwise.

Due to the extensive use of a wide array of PFAS, sampling crews should review all materials and sampling protocols to avoid contamination and possible sorption issues. Examples of materials that, if used and contacted, samples could potentially introduce bias include, but are not limited to:

- polytetrafluoroethylene (PTFE)
- waterproof coatings containing PFAS
- fluorinated ethylene-propylene (FEP)
- ethylene tetrafluoroethylene (ETFE)
- low-density polyethylene (LDPE)
- polyvinylidene fluoride (PVDF)
- pipe thread compounds and tape.

A tiered approach should be implemented for materials restrictions, where the first tier would include restrictions on the sampling materials that will come in direct contact with the sample media, and the second tier would include restrictions on what materials are allowed on sampling personnel or within the staging area. The focus on restrictions within the second tier should consider how reasonable the potential for contact with the sample media is when good sampling practices are employed, the practicality of the restriction (for example, does it compromise employee safety or increase an exposure risk), and the documentability of the requirement (can the restriction or measure be properly documented). Program-specific sampling protocols such as those previously listed in this section often identify materials and equipment that can be used in PFAS-focused investigations, as well as materials that should be avoided because they are known or suspected to be potential sources of PFAS. However, as noted in peer-reviewed studies (Denly et al. 2019; Rodowa et al. 2020), the potential for cross-contamination from sampling materials that are not likely to contact the sample media or incidental contact (e.g., rain splatter off a treated raincoat) is minimal and the focus should be on material in direct contact with the sample media and with a reasonable potential for contact. It is also recognized that a PFAS-free alternative may not be readily available or confirmable. In such instances a robust quality assurance (QA) program consisting of appropriate equipment blanks can be implemented to address this.

There may be instances when it is not possible to eliminate sampling materials that may affect sample results. For example, problematic materials may be needed at sites where co-contaminant or facility hazards warrant the use of PPE such as Tyvek suits or flame-retardant coveralls for worker safety. Additionally, this could be an issue in emergency response scenarios if a sampler needs to collect a sample before a proper program is established or before proper sampling materials can be obtained.

11.1.3 Bottle Selection

Sample container material recommendations are dependent on the analytical method. Containers should be supplied by the laboratory and laboratory-verified to be PFAS-free, as defined by the work plan. USEPA SW-846 Method 8327 was validated using polypropylene containers for groundwater, surface water, and wastewater sampling. However, USEPA SW-846 Method 8327 states that other types of containers such as high-density polyethylene (HDPE) may be used if the needs of the project can be met with their use. USEPA Method 533 and USEPA Method 537.1 require the use of polypropylene or other plastic containers, such as polyethylene, that meet the QC requirements (Section 11.1.7.1). USEPA Draft Method 1633 requires the use of HDPE containers for wastewater, groundwater, surface water, landfill leachate, biosolids, soil, sediment, and tissue sampling.

The volume of aqueous sample that is required for analysis varies from method to method and the mass of solid material required for analysis in accordance with USEPA Draft Method 1633 is dependent on the matrix of the sample.

Non-potable water samples do not require a chemical preservative (USEPA Draft Method 1633), unless otherwise required by the cited analytical method(s). Clean laboratory-provided HDPE or polypropylene bottles are recommended; typically, 125-mL to 1-L bottles may be used, but the sample volume may depend on the analytical method used.

In USEPA Draft Method 1633, samples are prescreened to determine if they contain high concentrations of PFAS analytes or other potential interferences (e.g., landfill leachates) that would prohibit the whole aqueous sample from being prepared. The method allows for a smaller aliquot of wastewater, groundwater, or surface water than collected for analysis to be collected for prescreening analysis and determination of percent suspended solids. This second aliquot allows the laboratory to prescreen the sample without affecting the integrity of the sample collected for analysis. Coordinating with the laboratory is crucial to ensure an adequate number of each type of required sample container is provided for the field activity.

Best practices in sample preparation should be used when selecting the size, volume, and representativeness of samples. To minimize effects from analyte sorption on sample containers, USEPA Methods 537.1 and 533, and USEPA Draft Method 1633 all require the laboratory to prepare the entire aqueous sample collected, including sample container rinsate(s). DOD AFFF01 requires the container holding the diluted AFFF concentrate be prepared in its entirety, including a rinse of the container.

11.1.4 Sample Preservation, Shipping, Storage, and Holding Times

Sample preservation, shipping, storage, and holding time requirements are dependent on the method used. Drinking water methods (USEPA Method 537.1 and 533) are the only USEPA methods requiring the addition of a chemical preservative at sample collection. USEPA Method 537.1 requires the addition of Trizma®, while USEPA Method 533 requires the addition of ammonium acetate, as detailed in section 8 of each of the methods. According to both methods, samples must be chilled during shipment and not exceed 10°C during the first 48 hours after collection. When they are received by the laboratory, samples must be at or below 10°C and stored in the laboratory at or below 6°C until extraction. These two methods differ in their required holding times, as USEPA Method 537.1 requires samples to be extracted within 14 days of collection, while USEPA Method 533 requires samples to be extracted within 28 days of collection.

The shipping, storage, and holding time requirements for wastewater, groundwater, and surface water samples stated in USEPA SW-846 Method 8327 differ than those provided by USEPA Draft Method 1633. USEPA SW-846 Method 8327 requires all samples and sample extracts to be chilled from the time of sample collection to analysis and not exceed 6°C. Since a holding time study was not performed in conjunction with the validation of USEPA SW-846 Method 8327, the method offers a holding time of 14 days from sample collection to sample extraction and a 30-day holding time from sample extraction to sample analysis as a guideline.

The shipping, storage, and holding time requirements contained in USEPA Draft Method 1633 are based on a published holding time study for PFAS in wastewater and surface water (Woudneh et al.2019) and the results of a holding time study conducted in conjunction with the single-laboratory validation study of USEPA Draft Method 1633. The holding time study performed during this validation study assessed what impact, if any, two storage temperatures had on 40 PFAS in wastewater, groundwater, surface water, soil, sediment, and biosolids samples and sample extracts. The recovery of 40 PFAS in samples stored at -20°C and 4°C and extracts stored at 4°C was evaluated at defined intervals over the course of 90 days. While the statistically determined holding time requirements are similar for each matrix, they are not identical (see Table 11-5, included in the PFAS Analytical Methods Excel File). Observed losses and/or gains in the concentration of some PFAS, most likely caused by transformation of precursors, resulted in shorter holding times for samples and extracts held at 4°C as opposed to -20°C. Due to the observed extreme loss of NFDHA, an additional caveat in the method recommends samples be extracted and analyzed as soon as possible if NFDHA is an important analyte for the project.

11.1.5 Decontamination Procedures

Sampling equipment should be thoroughly decontaminated before mobilization to each investigation area and between sample locations at each investigation area or as required in the site-specific work plan. Field sampling equipment, including oil/water interface meters, water level indicators, nondisposable bailers, and other nondedicated equipment used at each sample location requires cleaning between uses. The SDSs of detergents or soaps used in decontamination procedures should be reviewed to ensure fluorosurfactants are not listed as ingredients. Use laboratory-verified PFAS-free water for the final rinse during decontamination of sampling equipment. Decontaminate larger equipment (for example, drill rigs and large downhole drilling and sampling equipment) with potable water using a high-pressure washer or steam. To the extent practical, rinse parts of equipment coming in direct contact with samples with PFAS-free water. Heavy equipment is best cleaned within a decontamination facility or other means of containment (for example, a bermed, lined pad and sump, or a portable, self-contained decontamination booth). Potable water sources should be analyzed in advance for PFAS, as well as during the sampling event. If the potable water source does not meet the project-defined criteria for PFAS-free water, an alternate water supply should be considered. Wherever possible, rinse equipment with laboratory-verified PFAS-free water immediately before use.

An example of decontamination procedures as published in the Minnesota Pollution Control Agency “Guidance for Per- and Polyfluoroalkyl Substances (PFAS): Sampling” (MPCA 2022) is as follows:

- Equipment caked with drill cuttings, soil, or other material will initially be scraped or brushed. The scrapings will be collected, containerized, and disposed in accordance with government regulations.
- Equipment will then be sprayed with potable water using a high-pressure washer.
- Washed equipment will then be rinsed with laboratory-verified PFAS-free water.
- Decontaminated downhole equipment (for example, drill pipe, drive casing, bits, tools, bailers, etc.) will be placed on clean plastic sheeting (PFAS-free) to prevent contact with contaminated soil and allowed to air dry. If equipment is not used immediately, it will be covered or wrapped in plastic sheeting to minimize airborne contamination.
- Field sampling equipment and other downhole equipment used multiple times at each sample location will

> require cleaning between uses utilizing a four-stage decontamination process. The equipment will first be rinsed in a bucket containing a mixture of potable water and PFAS-free soap. The equipment will then be rinsed in each of two buckets of potable water. Water used for the final rinse during decontamination of sampling equipment will be laboratory-verified PFAS-free water.

Decontamination solutions should be replenished between sampling locations as needed. Spent decontamination fluids should be containerized, properly labeled, and appropriately disposed of as investigation-derived waste (IDW), based on plans included in the site-specific QAPP or work plan.

11.1.6 Field QC Samples

Field QC samples are a means of assessing quality beginning at the point of collection. Such field QC samples typically include field reagent blanks, source water blanks, equipment rinse blanks, and field duplicates. Collection and analysis of field QC samples are important for PFAS investigations because of very low detection limits and regulatory criteria (parts per trillion (ppt)), to ensure accuracy and representativeness of the results for the sampled media, and to assess potential cross-contamination due to the extensive use of PFAS. A sampling program should be designed to prevent cross-contamination and anthropogenic influence. However, the widespread commercial use (historical and current) of PFAS-containing products, and especially their prevalence in commonly used sampling materials and PPE, should inform the sampling program. PFAS sites may also have a wide range of concentrations with varying families of PFAS, as well as co-contaminants. Furthermore, PFAS sites have the potential to be high profile in nature. Therefore, a comprehensive site-specific QAPP or work plan addressing DQOs and field QC samples, including frequency, criteria, and procedures, is vital to a PFAS sampling program (see also Section 11.3, Data Evaluation).

When planning QC sample frequency, the risk of cross-contamination should be considered. Cross-contamination can occur from several sources, including field conditions, ineffective decontamination, incidental contact with PFAS-containing materials, and sampling equipment and materials that were manufactured alongside PFAS-containing equipment.

Of all the USEPA PFAS methods, only USEPA Methods 537, 537.1 and 533 contain specific requirements for the field QC samples that must be collected and accompany samples to be analyzed for PFAS. These include field duplicates, matrix spikes and duplicates, and a minimum of one field reagent blank for each set of samples per sampling site. USEPA Methods 537, 537.1 and 533 specify the frequency of the field duplicate or matrix spikes in terms of extraction batch (one per extraction batch, not to exceed 20 field samples), not collection frequency. Although the other USEPA PFAS methods do not contain any field QC sample requirements, Table 11-1 provides a list of field QC samples typical for the collection of these matrix types and their typical minimum frequency. Once field QC sample data are obtained, they should be evaluated against the field samples by a person knowledgeable on the DQOs set forth in the site-specific QAPP or work plan. For laboratory QC considerations, see Section 11.2, Analytical Methods/Techniques.

Table 11-1. Typical field QC samples

QC Sample	Description	Minimum Suggested Frequency
Field reagent blank (FRB)	Laboratory-provided PFAS-free reagent water that, in the field, is poured into an empty sample bottle or a sample bottle containing only preservative (if required)	One per day per matrix per sample set
Source water blank	Water collected from potable water source that is used during the sampling processes (such as decontamination and drilling processes)	One per site, preferably prior to sampling event (if possible) and at least once during sampling event
Equipment rinse blank (ERB)	Final rinse sampling equipment with laboratory-verified PFAS-free water (decontamination blank); prior to the sampling event	One prior to the start of a sampling event per piece of sampling equipment following an initial decontamination One per day per piece of sampling equipment used for each matrix sampled (during or at the end of the day) following decontamination
Field duplicate	Two samples collected at the same time and location under identical circumstances	One per day per matrix, or one per 20 samples per matrix, whichever is greater

11.1.6.1 Field Reagent Blank

A field reagent blank (FRB), as described in USEPA Methods 537, 537.1 and 533 for collection of drinking water samples, consists of a sample bottle filled with PFAS-free reagent water prepared in the laboratory, sealed, and shipped to the sampling site along with the sample bottles. An empty sample bottle containing only preservatives (same as those used for the samples) is also shipped along with each FRB into which the sampler pours the unpreserved PFAS-free reagent water contained in another bottle that was sent to the field and seals and labels the bottle for shipment along with the samples back to the laboratory for analysis. FRBs help to determine if PFAS were introduced into the samples during sample collection/handling and help to account for additional factors, such as introduction of contaminated airborne particles. A laboratory reagent blank is also analyzed in a laboratory setting to ensure that background contamination is not being introduced in the laboratory from reagents or water supplies.

FRBs may also be warranted during collection of sampling media other than finished drinking water. In lieu of using a prepared quantity of laboratory reagent water/preservative solution as for drinking water FRB, a field blank can be prepared in the field using laboratory-verified PFAS-free water (may be equivalent to the laboratory reagent water) and filling an empty sample container in the field, which is then sealed and labeled as a field blank. This sample will be analyzed in the same manner as the normal samples and can indicate whether or not PFAS were introduced during sample collection/handling, and help to account for additional factors, such as introduction of airborne particulates.

As discussed above, the frequency of FRB samples for finished drinking water sampling is one FRB for every sample set at each site. A sample set is described in USEPA Methods 537.1 and 533 as “samples collected from the same sample site and at the same time” (USEPA 2020; USEPA 2019).

11.1.6.2 *Source Water Blank*

Large quantities of water may be necessary to carry out a field sampling program for various reasons, including decontamination and certain drilling techniques (Section 11.1.5, Decontamination Procedures). Site groundwater or surface water should not be used as source water at sites that are under investigation for PFAS, as they have potential to contain PFAS. PFAS test results of publicly supplied water at a site should be evaluated when considering it for use as source water. Regardless, it is imperative that any water used as source water be sampled and analyzed. For equipment that may come into contact with samples of any media type, a multistep process is common to adequately prevent cross-contamination. Quantities of laboratory-verified PFAS-free water are generally limited and can be costly. Therefore, potable water sources are typically used in initial decontamination steps. It is imperative that these water sources be sampled and analyzed in the same manner as normal samples, prior to and even during a PFAS sampling program, to ensure that source water is not contributing to PFAS detections in normal samples. Further, many laboratories do not provide a verification of the laboratory-supplied DI water being PFAS-free unless specifically requested. Submission of a laboratory deionized water blank could be required based on DQOs of the specific project.

Collect a sample from the source the same way it is collected for use (for example, if the source water is collected through a hose, collect the source water blank from that same hose). If there are unnecessary fittings or hoses attached for collection of the source water, consider removing them for the duration of the sampling program to avoid contamination from PFAS that may be present in these materials.

Frequency of collection of such source water blanks is up to the professional judgment of the project manager, site owner, and other stakeholders and is detailed in the project-specific work plan. The source water should be sampled at least once prior to starting the field sampling program and once during the sampling event in case the analysis reveals that a different water source should be found. A more conservative sampling program may include provisions for additional periodic sampling in cases where the conditions of the source water may change.

11.1.6.3 Equipment Rinse Blank

Equipment Field Blanks (ERB) should be collected from nondedicated equipment/supplies at the start of the sampling event prior to sample collection to verify that nondedicated equipment/supplies are PFAS-free (Section 11.1.2). Thereafter, ERBs should be collected from nondedicated sampling equipment at a minimum rate of once per day (either during or at the end of each day) following decontamination and prior to its next use for the duration of the sampling event.

ERBs are those collected by rinsing a piece of field sampling equipment/supplies with laboratory-verified PFAS-free water and collecting the rinse water in a sample container for PFAS analysis. ERB collection is not required by USEPA Methods 537.1 or 533 because drinking water compliance samples are generally collected from the source without the use of other equipment. ERB collection for other programs is dependent on the sampling media and methods that are employed at a site. Generally, any equipment that is reused throughout the sampling program, or is nondedicated, and must be decontaminated, should have an ERB collected from it. That is, if a piece of equipment is decontaminated, an ERB should be collected from it after decontamination and prior to its next use. The frequency of collection of ERBs can be reduced by using all dedicated or disposable equipment where possible. However, many of these options are limited due to the extensive use of PFAS in many of these equipment materials. ERBs should also be considered for dedicated equipment prior to and during a sampling event if the PFAS contribution from equipment is unknown or suspected.

Field ERB collection frequency is largely up to the professional judgment of the project manager or other stakeholders and is dependent on the sampling media and methods and project-specific DQOs. For instance, collection of ERBs prior to initiating an event may be appropriate if rental equipment or subcontractor material that could have been used on another site is being used. The project team may also consider collecting an ERB from each piece of equipment used by the sampling team (ERB per sample setup) when multiple sampling setups are being implemented. Collection of an ERB from decontaminated soil sampling trowels may only warrant a frequency of once per day, whereas groundwater pumps may warrant an ERB prior to the pump being deployed down each well, due to their more rigorous decontamination procedure and higher contact time with the groundwater being sampled.

11.1.6.4 Field Duplicate

Field duplicate (FD) samples are two samples collected at the same time and location under identical circumstances and treated exactly the same throughout field and laboratory procedures. The analytical results from these identical samples are used to evaluate the precision of sample collection, preservation, storage, and laboratory methods.

USEPA Methods 537.1 and 533 do not specify the frequency of FD collection for finished drinking water samples; however, they do specify the frequency of preparation (once per extraction batch, not to exceed 20 field samples). A more conservative sampling program may indicate a frequency of one FD per 10 field samples per matrix. FD collection frequency should be discussed with stakeholders as necessary and be evaluated as part of the comprehensive site-specific QAPP or work plan.

11.1.6.5 Additional QC Samples

In addition to the field quality control samples described above, replicate volume or mass may be collected for split samples and/or matrix spikes to provide project managers additional quality assurance regarding identification of PFAS target analytes and precision and bias in measured sample concentrations. Split samples are defined here as co-located quality control samples, taken at the same time and each sent to a different laboratory. These types of samples do not apply to routine compliance monitoring situations and may not be required in all sampling events. Aqueous QC samples should not be split into two samples from the original container. Analysis of these QC samples provides a measure of interlaboratory variability.

A performance evaluation (PE) sample, which contains project analytes with known concentrations of PFAS, may be submitted to the laboratory as a blind sample. Analysis from this sample provides a positive control from a second source.

11.1.7 Sampling Procedures

Standard sampling procedures and practices can be used at most PFAS sites and only require extra care and attention paid to the types of materials used. However, there may be some exceptions and additional considerations related to PFAS behavior and issues associated with potential use of PFAS-containing or PFAS-adsorbing sampling equipment and supplies, as previously discussed. A site-specific QAPP or work plan must contain the standard operating procedures incorporating these considerations and regulatory agency or client requirements. Refer to Section 11.1.2 for materials to avoid during sampling and drilling. Consult the supplier to determine if PFAS-free options are available.

Pretesting any equipment or supplies to be used is ideal though it is recognized that this is not typically feasible. As such, ERBs are recommended to ensure the decontamination of supplies (for example, bailers, pumps, beakers, and dippers) is effective.

In addition, the sampling team must document any observations during the sampling event that could be a source of bias (for example, the presence of PTFE tape on a faucet).

11.1.7.1 Drinking Water

Sampling a “potable water source,” as defined by the USEPA SDWA (Section 1401(4), August 1998), is conducted according to protocols established in USEPA Methods 537.1 and 533. These protocols define sample bottle preparation, sample collection, field reagent blanks, sample shipment and storage, and sample and extraction holding times. The drinking water source is further defined here as a public drinking water supply, as opposed to a private drinking water supply, as it applies to USEPA Methods 537.1 and 533. USEPA Methods 537.1 and 533 may also apply in instances when the water quality of the private drinking water supply source is similar to finished drinking water (for example, has low level of total organic content). The following summarizes the sampling considerations described in these protocols:

- For Methods 537 and 537.1: Sample bottle is a laboratory-provided 250-mL polypropylene bottle fitted with a polypropylene screw cap. For finished (treated) drinking water sampling only, a preservation agent is provided inside each bottle prior to sample collection. This agent acts as a buffer (Trizma®, pH 7, 5 g/L) and removes free chlorine from chlorine-treated drinking water supplies.
- For Method 533: Sample bottle is a laboratory-provided 100–250-mL polypropylene, or other plastic that meets method QC requirements, bottle fitted with a polypropylene screw cap. For finished (treated) drinking water sampling only, a preservation agent is provided inside each bottle prior to sample collection. This agent (ammonium acetate, 1 g/L) sequesters free chlorine to form chloramine in chlorine-treated drinking water samples. The sample handler must avoid PFAS contamination during sampling by thoroughly washing their hands and wearing nitrile gloves.
- Open the tap and flush the water (approximately 3–5 minutes) to obtain a “fresh” sample. Collect the sample while water is flowing, taking care not to flush out preservative. Samples do not need to be headspace-free. Cap the bottle and, if applicable, agitate to completely dissolve preservative.
- Keep sample sealed and place sample on ice for shipment.
- Samples must be chilled during shipment and must not exceed 10°C during shipment.
- Laboratory extraction of the sample must take place within 14 days of collection (USEPA Method 537.1) or within 28 days of collection (USEPA Method 533).

Based on a review of industry experience and guidance, additional considerations for collecting drinking water samples for PFAS analysis are as follows.

- The sample should be collected from a cold tap or spigot located at or near the wellhead or pump house and before the water supply is introduced into any storage tanks or treatment units. If the sample must be collected at a point in the water line beyond a tank, a sufficient volume of water should be purged to provide a complete exchange of fresh water into the tank and the tap or spigot. If the sample is collected from a tap or spigot located just before a storage tank, spigots located downstream of the tank should be turned on to prevent any backflow from the tank to the tap or spigot. Several spigots may be opened to provide for a rapid exchange of water. If collecting a sample to characterize human or other exposure, the sample should be collected from the tap or spigot at the point of use.
- When sampling from a drinking water well that is not in regular use, purge water until water quality parameters (that is, pH, specific conductance, dissolved oxygen, oxidation-reduction potential, turbidity, and temperature) have stabilized according to project-specific requirements, to ensure formation water (as opposed to stagnant well column water) will be sampled. An adequate purge is achieved when the pH and specific conductance of the potable water have stabilized (for example, within 10% across three consecutive measurements) and the turbidity has either stabilized or is below 10 nephelometric turbidity units. Note: According to USEPA (2013), pg. 21 *“[a] well with an intermittently run pump should, in all respects, be treated like a well without a pump. In these cases, parameters are measured and the well is sampled from the pump discharge after parameter conditions have been met. Generally, under these conditions, 15 to 30 minutes will be adequate.”*
- When sampling from a tap, the tap must be protected from exterior contamination associated with being too close to a sink bottom or to the ground. Contaminated water or soil from the faucet exterior may enter the bottle during the collection procedure because it is difficult to place a bottle under a low tap without grazing the neck interior against the outside faucet surface. If the tap is obstructed in such a way that prevents direct collection into the appropriate sample container, it is acceptable to use a smaller container to transfer sample to a larger container. The smaller container should be made of HDPE or polypropylene and should be either new or decontaminated as specified in Section 11.1.5. Evaluation of the transfer container is recommended to ensure that it does not introduce a bias.
- When filling any sample container, care should be taken that splashing drops of water from the ground or sink do

not touch either the interior of the bottle or cap.

- Leaking taps that allow water to discharge from around the valve stem handle and down the outside of the faucet, or taps in which water tends to run up on the outside of the lip, are to be avoided as sampling locations.
- Disconnect any hoses, filters, or aerators attached to the tap before sampling.

Taps where the water flow is not constant should be avoided because temporary fluctuation in line pressure may cause clumps of microbial growth that are lodged in a pipe section or faucet connection to break loose. A smooth flowing water stream at moderate pressure without splashing should be used. The sample should be collected without changing the water flow.

11.1.7.2 Groundwater

Groundwater is typically sampled from a well, and therefore specialized equipment is required. When constructing monitoring wells prior to groundwater sampling, care should be taken to ensure well-construction materials are free of PFAS. Radford et al. (2023) detected PFAS in coated and uncoated bentonite formulations with more individual PFAS present at higher concentrations in coated formulations. PFAS have also been added to various concrete formulations (Kissa, 1994). Drilling greases, grout, and all well construction materials should be confirmed to be PFAS-free prior to use. Additionally, water added to the formation for drilling purposes (mud mixtures, managing running sands, etc.) may need to be tested for PFAS prior to use and should be thoroughly developed out of the completed well prior to sampling. Some of the various types of purging and sampling equipment available for groundwater sampling are described in ASTM International Standard Guide for Sampling Ground-Water Monitoring Wells, D 4448-01 (ASTM 2007) or Compendium of Superfund Field Operations Methods (USEPA 1987).

Within the context of sample collection objectives outlined in a site-specific work plan, the sample depth selection should consider the potential stratification of PFAS within the aquifer, the potential for phase partitioning, and the tendency for PFAS to accumulate at the air/water interface. In addition to depth location within the water column, consideration should be given to the well construction, screened interval, and site geology to ensure that the well is representative of site conditions and all relevant chemicals of concern (COCs). For more information on phase partitioning, see Section 5.2.

The most inert material (for example, stainless steel, silicone, polypropylene, and HDPE), with respect to known or anticipated contaminants in the well(s), should be used whenever possible. Purging and sampling equipment could be manufactured from components that might include PFAS. For example, pump components, such as O-rings, gaskets, bladders, stopcocks, and wiring insulation, may contain PFAS. Contact between the groundwater, and/or the sample, and PFAS-containing equipment provides opportunities for the sample to become contaminated and should be avoided when possible. In some cases, components that contain PFAS can be switched out for HDPE or polyethylene. Consult with the equipment vendor to determine if they have PFAS-free alternatives. In addition to equipment, ensure that field supplies that may contact the sample, such as tubing or bailer twine, are PFAS-free and will meet the DQOs. Dedicated sampling equipment installed in existing wells prior to PFAS investigations may contain components that are not PFAS-free, and the equipment’s chemical properties may be challenging to verify. It is best practice not to collect samples using dedicated equipment that may include PFAS-containing components. If samples are collected with dedicated equipment with some unknown components, PFAS detections should be evaluated in an uncertainty analysis.

Where sampling for co-contaminants requires use of PFAS-containing materials, sampling events should be separated to avoid contamination from these materials. The PFAS sampling event would be completed first, followed by the sampling event for the co-contaminants. In some cases, it may be acceptable to use the same equipment at a concurrent sampling event. For circumstances that warrant, such as very deep wells or sites with co-contaminants, samples may be collected in duplicate with and without existing dedicated equipment. If PFAS analyses show that the equipment does not impact results, the equipment may be kept and used long term. However, this determination is dependent upon project-specific requirements and should be allowed by a project manager only with full disclosure to all stakeholders. It may also be acceptable to simply collect an ERB after fully decontaminating equipment containing PFAS components to confirm it does not contribute to groundwater sample concentrations. A site-specific procedure should be outlined in the QAPP or work plan.

The practitioner should determine that the sampling method is compatible with the site DQOs, including whether the method:

- collects site-specific analytes of interest
- is effective at the expected concentrations
- provides sample volume that meets the lab method requirements

- minimizes turbidity
- minimizes purge water
- is likely to include equipment with PFAS-containing components that contact the sample

Low-flow or passive sampling techniques are preferred for collection of groundwater samples for PFAS to keep the turbidity of samples and purge-water volume to a minimum. PFAS are mobile in groundwater and have relevant transport pathways, including advection and diffusion, that are similar to those for other contaminants (Section 5.1.2) and conducive to passive sampling (Section 11.1.7.6) in groundwater. See Section 11.2.1.2 for issues associated with elevated levels of suspended solids in aqueous samples.

Bailers should be used with caution due to the potential for PFAS to accumulate at the air/water interface, because they may increase turbidity, and because of the potentially large volume of purge water produced. If bailers are used, it is important to make sure that at least three well volumes are purged to remove static surface conditions and potentially stagnant or aerated water. Volume-purge pump sampling for PFAS is discouraged because of the large amounts of purge water generated and the tendency to increase turbidity.

For background guidance on the use of passive sampling, consult the ITRC's prior technical guidance document (ITRC 2007) which, in addition to equilibrium-based diffusion sampling (see also Section 11.1.7.6), provides guidance on passive, no-purge grab-samplers that collect a whole-water sample.

Samples should not be filtered, because filters may be either a source for contamination (Ahrens et al. 2009; Arp and Goss 2009) or PFAS may be adsorbed to the filter. If filtration is absolutely necessary, it should be performed in the laboratory, using a validated procedure that includes steps to eliminate the bias that can occur due to sorption issues. As an alternative, laboratory-validated procedures may include centrifuging the sample due to potential filter sorption or contamination issues. See Preparation of Aqueous Samples with Particulates/Suspended Solids in Section 11.2.1.2 for more details. In addition, USEPA Draft Method 1633 strongly discourages composite sampling for Clean Water Act compliance monitoring, stating that samples from sources that flow freely are to be collected as grab samples.

11.1.7.3 Surface Water

Surface water PFAS sampling should be conducted in accordance with traditional methods such as those described in USEPA's Compendium of Superfund Field Operations Methods (USEPA 1987) with consideration for recently developed guidance specifically for PFAS by Michigan EGLE (MI EGLE 2021) and New York Department of Environmental Conservation (NY DEC 2021). Depending on the study objectives, sample collection should consider the potential stratification of PFAS in the water body and the tendency for PFAS to accumulate at the air/water interface due to partitioning, which will be of particular concern if foam is observed on the surface (see Section 16.5 on PFAS-containing foam). Transfer containers such as beakers or dippers, which may be attached to extension rods, should be used. For additional information on surface water sampling, see Section 16.4.

- Within the context of sample collection objectives outlined in a site-specific QAPP or work plan, the sample location in the water column should consider the potential stratification of PFAS in solution and their tendency to accumulate at the air/water interface (see Sections 5.2.2.2 and 5.2.4.1). If possible, the sample container or transfer container will be lowered sufficiently below the water surface but above the bottom sediments.
- Transfer containers, such as beakers or dippers, which may be attached to extension rods, should be used only if sample containers have preservatives. Sampling by direct sample container immersion is not recommended in this case.
- Consider using a grab-sampler that seals the sample inside the device at the sample interval and isolates the sample from contact with water above the sample collection interval as the sampler is being removed.

11.1.7.4 Sediment Porewater

Similar in many ways to sampling techniques and equipment used in groundwater sampling for PFAS, porewater purging and sampling involves a variety of materials. The various types of purging and sampling equipment available for porewater sampling are described in *Pore Water Sampling Operating Procedure* (USEPA 2013). For PFAS sampling, peristaltic pumps with silicon and HDPE tubing are typically used for porewater sample collection, along with push-point samplers, porewater observation devices (PODs), or drive-point piezometers. Push-point samplers and drive-point piezometers are made of stainless steel, while PODs consist of slotted PVC pipe and silicon tubing. PODs and drive-point piezometers are permanent, or dedicated, sampling points typically installed and used for multiple sampling events, whereas push-point samplers are used as a temporary sampling location. Otherwise, the standard procedure for porewater purging and sampling using a peristaltic pump, as described in the *Compendium of Superfund Field Operations Methods* (USEPA 1987), can be followed. There is recent information on the development and commercialization of various diffusion-based passive samplers that may be an option to sample porewater within sediment (see Section 11.1.7.6). Installing samplers at interfaces between coarse and fine materials can capture perched porewater (ASTM 2018, section 7.5.2.8). This is consistent with the modeling work by Zeng and Guo (2021) described in Section 10.4.1 in which PFAS was predicted to be found in perched water above capillary barriers.

11.1.7.5 Soil Porewater and Potential Lysimeter Use

The accurate characterization of PFAS in soil porewater within the vadose zone could provide valuable data for understanding the soil-water distribution of PFAS and its impact on groundwater concentration (see Section 10.4.1). One method that has been discussed is the use of lysimeters.

Lysimeters are devices installed within unsaturated soils that sample porewater either actively under positive and/or negative pressure (suction lysimeters) or passively during periods of excess drainage (drainage lysimeters). Lysimeters are widely available commercially and have been used as part of environmental investigations for decades (Singh et al. 2018). Early guidance documents on lysimeter sampling include USEPA (1986) and ASTM (2018).

Sampling of suction lysimeters should occur immediately after infiltration events such as rainstorms, spring melts, or irrigations to capture higher porewater and contaminant flow rates (USEPA 1986, section 4.8.1; ASTM 2018, section 7.5.2.8). Pan lysimeters, or nonsuction porewater sample collection devices, may be more suitable at sites where macropore flow is expected (USEPA 1986, section 4.8.2; and ASTM 2018, section 7.6.1.6).

Prior to installation, lysimeters should be cleaned per the vendor’s standard operating procedure, preassembled, and tested for air leaks. Typically, PVC pipe (equivalent to the depths of the borings) is attached to protect the sample tubes. If potential contaminant interactions with lysimeters is a concern, a laboratory study may be performed before installing at a site (USEPA 1986, section 4.8.3.2).

Like grab samples, lysimeter samples represent a single-time result and should be qualified as such when evaluating impacts to groundwater over a season or from year to year. Although suction lysimeter samples are good for qualitative comparisons, they cannot be used for quantitative PFAS investigation unless the variabilities of parameters involved are established (ASTM 2018, section 7.6.2.1). These parameters may include measured concentrations of PFAS in soil and porewater, as well as pH, permeability, total organic carbon (TOC), and anion and cation exchange capacity (AEC and CEC, respectively) in vadose zone soil; seasonal changes; weather; precipitation; depth; and soil type(s). Also consider measured PFAS concentrations in nearby groundwater wells.

There are limitations to the application of lysimeters, including on sites with:

- shallow groundwater at depths of around 5 feet or less from the surface (consult the manufacturer)
- bedrock that outcrops to the surface
- too little precipitation to result in sufficient soil moisture at depth
- insufficient co-located soil sample data including, but not limited to, TOC, pH, particle size, moisture content, CEC, and AEC

11.1.7.6 Passive Samplers in Aqueous Environments

Considerations for the use of passive sampling devices for PFAS may include the following:

- eliminates the problem of purge water disposal
- may reduce or eliminate turbidity as compared to pumped samples
- may reduce the cost of sample acquisition

Hydrogeologic conditions required for passive sampling (Imbrigiotta and Harte 2020 include:

- adequate water in the saturated screen/borehole so that the sample interval is submerged at all times
- saturated screens that are not chemically degraded or clogged
- adequate residence time for hydraulic (well flow) and chemical (contaminant concentration) equilibration

In most cases with saturated screens/boreholes 10 feet in length or greater, passive samplers are positioned at the depth of highest mass flux of the constituent of interest. When the interval of highest mass flux is not known, a one-time profiling event can be performed in representative wells using multiple passive samplers deployed at two or more intervals in the saturated screen. When considering transitioning from pumping to passive sampling in wells that have saturated screens 10 feet in length or greater, a favorable comparison of side-by-side results in representative wells suggests that water is being sampled from the same source location by both methods. When the results do not favorably compare, profiling for the interval of highest mass flux is appropriate.

A publication on the use of dual membrane passive diffusion bag samplers for PFAS (Varhol and Varhol 2022) provides results from bench and field tests that show a positive correlation with lab controls and with field samples taken by pumping methods.

Passive sampling methods can be selected to provide time-weighted average (TWA), time-integrated average, or instantaneous temporal data, as well as spatial contamination trends. Passive sampling devices (PSDs) are relatively low cost, simple to use, and do not generate IDW. Some passive samplers can also provide a means of correlating an organismal exposure with a biological effect to determine the biological importance of chemicals sampled by the device (Alvarez et al. 2021; Burki et al. 2006; Vermeirssen, Suter, and Burkhardt-Holm 2006).

There are several different approaches to passive sampling, most of which can broadly be categorized as either diffusion-based sampling or grab-sampling.

- Accumulation (integrative) devices concentrate the target chemical on a selective collecting medium such as an adsorbent or absorbent solid, a solvent, or a chemical reagent. Target molecules continue to accumulate on the collecting medium during the exposure period and do not come to concentration equilibration with the surrounding medium. The resulting sample mass, or flux, is used to calculate a TWA concentration of target compounds over the exposure period (Huckins, Petty, and Booji 2006; Taylor et al. 2021).
- Equilibrium devices use a semipermeable membrane to contain a collecting medium, which is usually a solvent such as deionized water. Target molecules that can diffuse through the selective membrane move from higher concentration to lower concentration, in and out of the sampler to maintain a dynamic equilibrium with the surrounding medium. After meeting a minimum residence time, usually 2–3 weeks, with no maximum residence time, samplers can be left in place at one event and recovered at another. The resulting aqueous sample represents the TWA concentration of target contaminants of the last few days prior to sampler retrieval.
- No-purge/passive grab samplers are devices that acquire a whole water sample in surface water or groundwater, at a specific interval. Once the sample is acquired, the sampler closes to isolate the sample from the surrounding fluids during retrieval. The resulting sample is an aqueous concentration representing the point in time when the sample was taken.

Practitioners have evaluated and used a variety of methods and devices for sampling PFAS in aquatic environments (Taylor et al. 2021; Imbrigiotta and Harte 2020; Alvarez 2010; Gong et al. 2018). A number of PSDs are currently in use and others are being investigated for monitoring PFAS in aquatic environments (Becanova et al. 2021; McDermett et al. 2022; Godlewska, Stepnowski, and Paszkiewicz 2020; Fauvelle et al. 2017; Kaserzon et al. 2012; Wang et al. 2021; Yang et al. 2022; Divine 2020; Varhol and Varhol 2022). Before using any passive sampling device, practitioners should ensure use of the proposed sampler has been validated with respect to the evaluation of the site-specific analytes of interest and is acceptable by the applicable regulatory agency.

11.1.7.7 Sediment

Most core and grab sampling devices are constructed of stainless steel. Some core samplers include an HDPE sleeve inserted in the core barrel to retain the sample. Ensure that materials that contact the media to be sampled do not have water-resistant coatings that contain PFAS that are the target of the analysis. Additional PPE may be required for sampling personnel, such as waders and personal flotation devices. Ensure that materials that will potentially contact sampling media do not consist of water-resistant coatings or other PFAS-containing materials or substances. Ensure efficient and consistent homogenization procedures are followed in the field. Refer to Section 11.1.2 for typical materials used during sampling and drilling.

11.1.7.8 Surface Soil

For surface soil sampling, refer to Section 11.1.2 for equipment and supplies, and Section 11.1.5 for decontamination procedures. Ensure efficient and consistent homogenization procedures are followed in the field. No additional considerations are recommended for PFAS sampling of surface soil.

11.1.7.9 Subsurface Soil

Ensure efficient and consistent homogenization procedures are followed in the field. No additional considerations are recommended for PFAS sampling of subsurface soil.

11.1.7.10 Biosolids

Biosolids sampling methods will vary based upon the state and homogeneity of the materials to be collected. Additionally, as the materials are often gathered and stored over days to weeks, varying PFAS concentrations in feedstock can cause varying concentrations within the biosolids matrix unless sufficient mixing is performed.

If high liquid content materials are stored for several hours or days, solids will settle from suspension. Mixing of the storage vessel prior to sampling is essential to ensure collection of representative materials. Dipper, bailer, or pump methods can be used to collect the samples from the midpoint of the storage vessel. If mixing cannot be performed, collection of multiple, stratified, liquid samples followed by compositing may be appropriate.

High solids content materials can often be sampled using traditional compositing techniques. Once again, the accumulation of biosolids over extended periods of time with varying feedstock characteristics can result in potential nonhomogeneous distribution of PFAS within the matrix being sampled. Nonhomogeniety can be reduced through thorough materials mixing and/or use of a high number of grab samples to form a composite for analyses.

For additional information regarding biosolid sampling plans, refer to the NEIWPCC Guide to Biosolids Sampling (NEIWPCC 2006) and the NEBRA PFAS Sampling (NEBRA 2020) Guidances.

11.1.7.11 Fish

The species of fish collected, as well as the portion of fish sampled (whole versus fillet), depends on the project goals (for example, ecological risk or human health). Studies have shown that the majority of the PFAS in fish are stored in the organs, not the flesh (Martin et al. 2004) (Yamada et al. 2014). Communicating project objectives to the laboratory is important prior to fieldwork to determine the necessary quantity and quality of tissue, fish handling requirements, laboratory sample preparation (including single fish or composite fish samples, and whole or fillet preparation), and packing and shipping requirements. According to USEPA Draft Method 1633, whole fish or other biota samples should be wrapped in aluminum foil or food-grade polyethylene wrap and homogenized tissue samples should be placed in HDPE containers.

11.1.7.12 Air Emissions to Air and Ambient Air

There is an increasing need for the measurement of PFAS in emissions from stationary sources (for example, chemical manufacturing, industrial use, combustion and thermal treatment and other treatment systems not originally designed to treat PFAS from exhaust), as well as in ambient air. Due to the diverse nature of PFAS, multiple measurement approaches are needed to measure polar and nonpolar, volatile, semivolatile, and nonvolatile (particulate-bound) PFAS.

Emissions to Air
Currently, there are no multilaboratory-validated sampling methods for PFAS in air emissions (for example, from thermal treatment in manufacturing plants or incinerators). In their absence, emissions measurements have been performed using modifications to USEPA SW846 Method 0010 (Modified EPA Method 5 Sampling Train) (USEPA 1986), a method designed for measurement of semivolatile organic compounds. Other methods have been adapted to capture specific individual compounds of interest.

USEPA and European groups (Verein Deutscher Ingenieure [VDI], an association of German engineers) are currently evaluating and investigating which sampling and analytical methods might be, in principle, the most suitable to capture PFAS and resulting byproducts in all fractions of the emissions (particles, moisture, gas phase).

PFAS can be partitioned in stack emissions into several different fractions due to the physical properties of these species. At the elevated temperatures typically encountered in stack emissions the vapor pressure can be sufficiently high that some PFAS are present in the gas phase. The lower molecular weight fluorotelomer alcohols (FTOHs) have lower boiling points and so may primarily be present as vapors. PFAS can adsorb to particulate matter, are highly water soluble, and can dissolve in water droplets if present in the stack. To measure these partitioned fractions, the stack effluent is sampled isokinetically (that is, the air enters the probe at the same velocity as it is moving in the stack, to accurately sample particles and droplets) and captured on a heated filter, an XAD-2 (polymer of styrene divinyl benzene) sorbent resin tube, and in water impingers. In some test programs a second XAD-2 sorbent cartridge is included in the sample train to determine if breakthrough has occurred. The filter, sorbent cartridge, and water impingers are recovered separately, and the sample train components are rinsed with a methanol/ammonium hydroxide solution.

In 2021, USEPA released Other Test Method (OTM) 45 *Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources* (USEPA 2021). This performance-based method was made available by USEPA as a recommended method that can be used to measure 50 specific semivolatile and nonvolatile polar PFAS from a variety of stationary sources. USEPA OTM-45 is largely based on the USEPA SW-846 Method 0010 (Modified EPA Method 5 Sampling Train) with several modifications. PFAS are collected in four sample fractions: 1) filter; 2) primary XAD-2; 3) impingers (containing water); 4) secondary XAD-2 (for breakthrough determination). Each fraction, with its associated rinses, is extracted and analyzed separately. Analyses are performed by isotope dilution LC/MS/MS. The analytical approach is based largely on EPA Method 533 and includes many of the same analytical qualification criteria, with the additional requirement of monitoring confirmatory secondary transition ions, similar to USEPA Draft Method 1633. USEPA OTM-45 was released as an “Other Test Method (OTM)” by USEPA’s Emission Measurements Center to promote consistency and is considered by USEPA to represent the current best practices to sample and analyze PFAS from stationary sources. This method is under evaluation and will be updated as more data from stakeholders become available. Field sampling programs must include collection of field blanks as a means of assessing PFAS artifacts present in sampling media and potentially introduced during sample handling in the field. Other QC measures that should be considered include the use of isotopically labeled PFAS field spikes. Field spikes are useful for quantifying losses associated with field collection techniques, since the lab has quantitatively spiked media used in the field and any losses can be measured. The isotopically labeled spike compounds are typically applied/spiked by the laboratory into the XAD-2 sorbent media prior to field deployment. These compounds serve to assess analyte (“native PFAS in air”) collection efficiency, breakthrough, and the accuracy of the combined sample collection and analysis method on a sample-specific basis.

Additional measurement approaches are needed to sample and analyze for other PFAS species, such as volatile and nonpolar PFAS, including PFAS that are specific to chemical manufacturing (for example, hexafluoropropylene oxide or HFPO). For example, some volatile (boiling point < 100oC) polar PFAS can be sampled by modified USEPA Method 18 *Measurement of Gaseous Organic Compound Emissions by Gas Chromatography* (USEPA 2017), in which the analytes are captured in chilled methanol impingers. The methanol reacts with some PFAS to form an ester which enables the capture and subsequent analysis. Other approaches include evacuated passivated canisters and sorbent traps for the more volatile PFAS species.

The ability to identify compounds not targeted for measurement by existing methods is an important need. Nontargeted analyses are critical to being able to identify these compounds. With nontargeted analyses, chromatography (liquid and gas) is combined with high resolution mass spectrometry and multiple ionization techniques to determine atomic molecular weight and associated fragments. These exact mass results can be used to calculate the molecular formula for tentative identification. Further spectral interpretation may result in structural identification. This is particularly useful where no chemical standards exist. USEPA Office of Research and Development (ORD) has used nontargeted analysis to support New Hampshire Department of Environmental Services and the Saint Gobain Performance Plastics emission characterization in Merrimack, New Hampshire. (NH DES 2019). It is anticipated that nontargeted analyses will be an important tool to thermal treatment research and the ability to identify potential products of incomplete combustion (PICs).

USEPA ORD is researching and evaluating multiple PFAS measurement approaches for polar and nonpolar, volatile, semivolatile and nonvolatile PFAS, including further development of USEPA OTM-45 for nonpolar PFAS. An additional method, OTM 50, is promised for delivery in 2023 to measure volatile PFAS. USEPA ORD is also evaluating the use of Fourier Transform Infrared (FTIR) spectroscopy to measure select volatile PFAS in real-time. Several of the PFAS capable of being measured are also being evaluated as potential indicators or surrogates of PFAS destruction performance.

Multiple PFAS emissions tests have been performed at a variety of sources for multiple purposes including source characterization, assessment of control technology performance, and evaluation of treatment technologies. Stationary source, or stack, emissions of PFAS have been measured in North Carolina (NC DEQ 2019) and New Hampshire (NH DES 2019) from industrial facilities that synthesized PFAS (Chemours, NC) or used PFAS in manufacturing processes (Saint Gobain Performance Plastics, NH) (Beahm and Marts 2019). These test programs confirmed that stack emissions from industrial facilities contribute to ground and surface water contamination (NC DEQ 2019). An additional study at Chemours, NC, reported on the commissioning of the recently installed thermal oxidizer control system (Weston Solutions, Inc. 2020).

Ambient Air

There are currently no USEPA Federal Reference Methods (FRM) or Toxic Organic Methods (TO series) available specifically for the measurement of PFAS in ambient air. In their absence, some sampling and analysis of ambient air have been performed using modified TO methods, such as TO-13A and TO-9 (USEPA 2020). Both methods use high-volume air samplers fitted with a particulate glass fiber filter/quartz fiber filter (GFF/QFF) and sorbent cartridge for the collection of particulate and gaseous phases, respectively. USEPA TO-13A specifies collection of air samples at a flow rate of approximately 225 liters/minute, resulting in an air volume greater than 300 m3. The solid sorbent used consists of a “sandwich” of polyurethane foam (PUF) and XAD-2.

PFAS in ambient air have been measured using both active (with actual flow) and passive (gas diffusion) sampling techniques. Most techniques have made use of solid sorbents such as PUF, XAD-2, and sorbent-impregnated PUF (SIP). (Finely ground XAD-4 resin is often the sorbent of choice for impregnating the PUF). Active samples also include a particulate filter (glass or quartz fiber) ahead of the sorbent module. To optimize detection limits, high-volume air samples have been used most often.

Detection limits of air and emissions methods can be greatly influenced by PFAS artifacts found in the neat filter, sorbent media, or components within the sampler itself. For example, use of Teflon gaskets in high-volume samplers is not recommended. Field sampling programs must include collection of field blanks as a means of assessing PFAS artifacts present in sampling media and potentially introduced during sample handling in the field. Other QC measures that should be considered include collection of field duplicate or co-located samples and the use of isotopically labeled PFAS field spikes. The latter compounds are typically applied/spiked by the laboratory into the sorbent media prior to field deployment. These compounds serve to assess analyte (“native PFAS in air”) collection efficiency, breakthrough, and the accuracy of the combined sample collection and analysis method on a sample-specific basis.

Passive samplers should also make use of mass-labeled PFAS as a sample-specific quality control measure to account for native PFAS losses during each sampling event. Volatilization of labeled PFAS during the deployment period provides sampling rates on a site-specific basis and accounts for both temperature and wind influences.

USEPA and European groups (VDI) are currently evaluating and investigating which sampling methods might be, in principle, the most suitable to capture PFAS and resulting byproducts in all fractions of the emissions (particles, moisture, gas phase). An important consideration is that fluorinated polymers are used in common sampling equipment, which may cause contamination of the samples. For the purposes of PFAS determinations, this material must be replaced. In addition to concerns over using fluorinated polymers in sampling equipment being a source of contamination, there are also concerns about the potential for sorption of PFAS to fluorinated polymers, thereby effectively reducing the observed concentration, or affecting any attempt to quantify the phase distributions between condensed and non-condensed phases (for example. PM vs gaseous). This is related, in part, to the concerns about quantification of ambient air concentrations and distributions, as published by Johansson, Berger, and Cousins (2017), showing that the use of GFF (and chemically deactivated glass fiber filters) may irreversibly bind fluoro-carboxylates during collection of samples containing fluoro-acids, which can be in the gas phase depending on their vapor pressure and ambient temperature, and the corresponding carboxylates. This issue for ambient air appears to negatively impact the estimates of phase distributions and so far, may not have a technique that is applicable for quantitative recovery (no answer to this problem has yet been published). A related issue, though separate from the ambient sampling confounding issues, is that quantification of acids/carboxylates via LC/MS does not/cannot distinguish between these two oxidation states, which is important to the phase distribution in ambient air (and emissions to air). There are other techniques (GC/MS or Chemical Ionization Mass Spectrometry (CIMS) (Riedel et al. 2019) that may help address these LC/MS deficiencies, particularly with regard to air measurements.

11.1.7.13 Human Blood, Serum, Tissue

Currently, there are no official or standardized methods for testing human blood, serum, or tissue. Laboratories and the Centers for Disease Control and Prevention (CDC) are in the process of developing best methods. A procedure developed by the CDC’s National Center for Environmental Health has been published (CDC 2016). There are also several laboratories advertising this capability; however, the analytical methods and modifications from validated environmental laboratory protocols may not be consistent among these vendors. Human testing is outside the scope of this document; however reference points that could be used for comparison of whole blood or serum results to geometric mean serum levels generated from the U.S. population are included in the ATSDR ToxGuide for Perfluoroalkyls (ATSDR 2020).

11.1.7.14 Potential High Concentration Samples

The CSM or historical data may indicate areas of high concentrations of PFAS for which single-use, disposable equipment is recommended. If single-use is not possible, take additional precautions such as implementing a greater frequency of ERBs and not reusing equipment to sample potentially low PFAS concentration samples. High concentration samples may require smaller sample volumes to be collected for analysis. High concentration samples should be segregated during shipping to the laboratory, and clearly identified on the sample chain-of-custody form.

Some projects may require the analysis of AFFF product that has been used at the site. All AFFF product samples must be considered high concentration samples. The method DOD AFFF01 contains steps to prepare AFFF concentrate samples. This method requires that a dilution of a subsample of the AFFF concentrate be prepared for extraction. A critical step in this procedure is the amount of time that must elapse, a minimum of 3 hours (Willey 2021) from the time PFAS-free reagent water is added to the aliquot of AFFF concentrate to create the dilution to the time when extracted internal standard can be added to the diluted sample. It was determined during method development and validation that some AFFF concentrates can take up to 3 hours to fully dissolve in the reagent water. In addition, this method requires each AFFF concentrate sample to be prepared and analyzed in duplicate, using another aliquot of the collected sample. It is recommended that these samples be segregated from other samples during sampling and shipping to avoid cross-contamination and clearly identified on the sample chain-of-custody form.

11.2 Analytical Methods/Techniques

11.2.1 Quantitative Techniques

11.2.1.1 General

Analytical methods are still evolving for PFAS analysis. Currently, very few methods are multi-laboratory validated and published. Three multilaboratory-validated methods, USEPA Methods 537, Version 1.1 (herein referred to as USEPA 537), 537.1, and 533 have been published for analysis of drinking water samples (USEPA 2009; USEPA 2020; USEPA 2019) and one, USEPA SW-846 Method 8327, has been published for analysis of groundwater, surface water, and wastewater samples. The DOD has published a multilaboratory validated method, DOD AFFF01 (Willey 2021), for the analysis of AFFF concentrates to demonstrate compliance to the military specification for AFFF (MIL-PRF-24385). The USEPA has published a single-laboratory validated method, USEPA Draft Method 1633 (USEPA 2022), for use for analysis of wastewater, groundwater, surface water, landfill leachates, soils, sediments, biosolids, and tissue. The USEPA released OTM 45 for measurement of PFAS in emissions to air from stationary sources. In April 2022, USEPA released the Draft Method 1621, Screening Method for the Determination of Adsorbable Organic Fluorine (AOF) in Aqueous Matrices by Combustion Ion Chromatography (USEPA 2022).

- USEPA Method 537, Version 1.1 tests for 14 PFAS analytes
- USEPA Method 537.1 tests for 18 PFAS analytes (including 4 PFAS not included in USEPA Method 533)
- USEPA Method 533 tests for 25 PFAS analytes (including 11 not included in USEPA Method 537.1)
- USEPA SW-846 Method 8327 tests for 24 PFAS analytes (does not include all PFAS included in USEPA Method 537.1 or 533)
- USEPA Draft Method 1633 tests for up to 40 PFAS analytes (includes all PFAS included in USEPA Method 537.1, 533, and 8327 and 11 additional PFAS analytes), depending on the matrix of the sample
- DOD AFFF01 tests for PFOA and PFOS
- USEPA Other Test Method (OTM) 45 tests for 50 specific semivolatile and nonvolatile polar PFAS
- ASTM D8421-22 Standard Method for Determination of Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous Matrices by Co-solvation followed by Liquid Chromatography Tandem Mass Spectrometry (LC/MS/MS)

Other methods have been published by other organizations. Lists of these methods, by various categories, are provided in the PFAS Analytical Methods Excel File in the **separate tabs**:

- External **Table 11-2**–Published Method Basics. Provides information on basic principles of each method (media type, validation status, method type, sample container requirements, holding time, preservation requirements, and analytical instrument.
- External **Table 11-3**–Published Methods Specifics. Provides more details of the methods such as sample preparation requirements, quantitation scheme, confirmation ion requirements, quantitation limits, and isomer profile.
- External **Table 11-4**–Provides summaries of the analyte lists for each of the methods. The method analyte list for each of these methods varies.
- External **Table 11-5**–Draft Published PFAS-Related Analytical Methods Basics. Provides information on basic principles of each method (media type, validation status, method type, sample container requirements, holding time, preservation requirements, and analytical instrument).

11.2.1.2 Sample Preparation

USEPA Methods 537, 537.1, 533, and Draft 1633, and DOD AFFF01 all require aqueous samples to be prepared using the solid-phase extraction (SPE) technique, but may use different solid-phase selectivities. USEPA Draft Method 1633 and DOD AFFF01 both require cleanup procedures be used on extracts and all associated batch QC samples to help eliminate matrix interferences (for example, bile salts, gasoline range organics) that could be present. USEPA Methods 537.1 and 533, USEPA Draft Method 1633, and DOD AFFF01 all require extraction of the entire sample collected (in the case of DOD AFFF01, the entire prepared dilution), including a rinse of the sample container (in the case of DOD AFFF01, the dilution container).

USEPA SW-846 Method 3512 is for the preparation of groundwater, surface water, and wastewater samples by diluting the sample collected with an equal volume of methanol and does not require a rinse of the sample container to be included unless the sample had to be transferred to a larger container in order to allow for the addition of the appropriate volume of methanol. USEPA SW-846 Method 3512 does not use SPE or carbon clean-up steps, which is another significant difference from the other USEPA published methods. USEPA SW-846 Method 8327 states that during method development, some PFAS analytes showed a potential for loss during sample preparation or standard preparation using USEPA SW-846 Method 3512. This method states that a minimum organic cosolvent content must be maintained in standards and samples, and it cautions against aqueous subsampling prior to adding sufficient organic solvent.

USEPA Draft Method 1633 prepares groundwater, wastewater, surface water, and landfill leachates using solid phase extraction (SPE) followed by carbon clean-up steps to eliminate matrix interferences. USEPA Draft Method 1633 uses solvent extraction for soil, sediment, biosolids, and tissue preparation, followed by use of SPE cartridges and carbon clean-up steps to eliminate matrix interferences. Regardless of the method used, care must be taken to prevent sample contamination during preparation and extraction because the limits of quantitation and detection are 1,000 times below (ppt) those for more routine analyses such as volatiles or semivolatile analysis (ppb). It is recommended that all supplies be checked and confirmed as PFAS-free prior to sample preparation. Intermittent contamination can occur due to vendor or manufacturing changes.

Some PFAS analytical methods, such as USEPA Method 533 and USEPA Draft Method 1633, use isotope dilution and extracted internal standard quantification schemes to calculate sample concentrations. Isotope dilution analysis (IDA) quantitation requires the use of extracted internal standards (EIS) that are the isotopically labeled analogs of the method analytes. Method analytes for which corresponding isotopically labeled analogs are not commercially available are quantitated using the isotopically labeled analogs of a method analyte of similar chemical properties. Since isotopically labeled analogs of PFOA and PFOS are commercially available, DOD AFFF01 uses isotope dilution quantitation. USEPA SW-846 Method 8327 uses an external quantitation scheme to calculate the percent recovery of isotopically labeled analogs that are added to the sample prior to dilution with methanol. This method does not use isotopically labeled analog recoveries to account for sample preparation and matrix interference biases in the sample result. All of the methods discussed above require these isotopically labeled standards be added to the sample at a designated point in sample preparation, depending on the sample matrix:

- aqueous samples–added to field samples while in the original container prior to extraction/dilution
- AFFF concentrates or high concentration aqueous samples – added to dilution of sample prior to extraction
- solid samples and biota–added after homogenization and subsampling, prior to addition of water or extraction solvent

Ensuring a representative sample/subsample for analysis is critical. For aqueous samples, the entire sample and rinsate of the sample container received by the laboratory must be extracted by SPE to recover any PFAS that adhere to the sample container. Filtration is not recommended for samples with high particulate content because retention of PFAS onto filters has been noted. Centrifugation is often used to reduce or separate out sample particulates. See Preparation of Aqueous Samples with Particulates/Suspended Solids below for more details.

USEPA Draft Method 1633 requires the screening of all aqueous samples using a separate sample container from the one which will be used for sample preparation. Due to limitations in SPE cartridge capacity and potential contamination of sample preparation and/or analytical equipment, the method requires samples containing high concentrations of PFAS (for example, AFFF concentrates) to be diluted prior to SPE and sample clean-up. In these cases, sorption onto the original sample container is not an issue, depending on the identified project-specific DQOs, because the amount of PFAS adsorbed onto the container walls may be negligible compared to the amount of PFAS in the sample.

USEPA Draft Method 1633 requires the entire soil, sediment, and biosolid sample that is collected be homogenized in the laboratory prior to subsampling. Tissue samples are to be prepared according to project requirements (for example whole fish versus fillet) and homogenized prior to subsampling.

Cleanup procedures can be used on extracts and all associated batch QC samples (for example, method blank and laboratory control samples) when matrix interferences (for example, bile salts, gasoline range organics) could be present. USEPA Draft Method 1633 and DOD AFFF01 require carbon cleanup techniques to be used for all sample matrices. USEPA Draft Method 1633 and DOD AFFF01 require samples to be slowly concentrated to remove methanol from the extract to avoid loss of neutral and other highly volatile method analytes. In addition, USEPA Draft Method 1633 states that if methanol is not sufficiently removed, its presence during SPE can result in poor recovery of long-chain carboxylic acids and sulfonates. Care must be taken to avoid these outcomes.

The preparation batch QC samples that are required by these PFAS methods vary. Common laboratory QC sample nomenclature and typical use frequencies are as follows:

- Method blank – (one per preparation batch of 20 or fewer field samples) PFAS are ubiquitous and found in many analytical instrument systems, reagents, containers, and common laboratory environments. The method blank is a similar matrix as associated field samples and undergoes the same sample preparation procedure as the associated field samples. It is a vital indicator of the absence of PFAS contamination in laboratory equipment, supplies, and reagents. Note that method blank is also referred to as Laboratory Reagent Blank in EPA drinking water methods.
- Sample duplicate – (minimum of one per preparation batch of 20 or fewer field samples) A sample that is prepared and analyzed in duplicate in a single laboratory to ensure the laboratory’s subsampling procedures are capable of achieving a known level of precision as defined in the QAPP or work plan.
- Laboratory control sample (LCS), ongoing precision and recovery (OPR), or laboratory fortified blank (LFB) – (typically one per preparation batch of 20 field samples) Must contain all project-specific PFAS in similar media as the associated field samples and is used to evaluate bias associated with sample preparation as well as analytical processes.
- Low-level laboratory control sample (LLLCS) or low-level ongoing precision and recovery (LLOPR) – (one per preparation batch of 20 field samples) Must contain all project-specific PFAS at a specified concentration (for example, 0.5–2 times the LOQ for USEPA SW-846 Method 8327 or 2 times the LOQ for USEPA Draft Method 1633) in similar media as the associated field samples and is used to evaluate bias associated with sample preparation as well as analytical processes.
- Certified reference material (CRM) – (if available, one per preparation batch of 20 or fewer field samples) Unlike LCSs, which contain no matrix interferences, CRMs can be of significant value when dealing with complex matrices such as soil, sediment, and tissue.
- Matrix spike (MS) and MS duplicate (MSD) – (one pair per prep batch of 20 or fewer field samples) An MS/MSD QC pair is not needed if IDA can be used for all PFAS of interest because the EIS recoveries account for the influence of matrix interferences in each sample, not just 1 in 20. If EIS standards are not available for a PFAS of interest, an MS/MSD QC pair may be warranted to assess the effects of matrix interference on that specific PFAS.

For samples with high concentrations of PFAS, it is recommended that an LCS duplicate and a sample duplicate are prepared in lieu of an MS and MSD. DOD AFFF01 requires the sample duplicate to be prepared using a different aliquot from the same sample bottle to create the sample duplicate.

Preparation of Aqueous Samples with Particulates/Suspended Solids

USEPA Draft Method 1633 contains a procedure for determining the solids content of aqueous samples. This determination is to be performed using the second container that is required for each sample, not the sample container used to prepare the sample for the analysis for PFAS. The sample preparation procedures for PFAS analysis in USEPA Draft Method 1633 are applicable to aqueous samples containing less than 50 mg of solids. The method provides additional steps to take if particulates clog the SPE cartridge during extraction, including the use of additional SPE cartridges. Solids accumulate high concentrations of PFAS and specifically some of the longer-chain PFAS. Care should be taken to resuspend any solids and to rinse bottles so that measured concentrations consider the entire sample.

When aqueous samples contain greater than or equal to 50 mg of solids, depending on the laboratory procedure, if the contaminant mass in the solids is not determined, the reported PFAS (fingerprint) could be inaccurate for effective comparison. Ultimately, the data user needs to work with the laboratory to determine the appropriate procedure to be performed, depending on the end use of the data (for example, remedial action, human health or ecological risk assessment, permit compliance, etc.). The project objectives may specify quantification of the total aqueous sample, water plus solids, or may only include evaluation of the aqueous fraction for end use as drinking water, where the solids will not be consumed.

A survey conducted in 2020 by ITRC received responses from 16 laboratories. These responses demonstrated that the laboratory community is *not* consistently preparing aqueous samples in the presence of suspended solids.

- Several laboratories centrifuge the samples and decant off the water portion for subsequent extraction.
- Some laboratories may also extract the remaining particulates and combine the extract with the aqueous extract. However, only one of the surveyed laboratories does this routinely; the others do this only if requested by the client.
- Routine laboratory procedures are not dependent upon whether the matrix is groundwater, surface water, or wastewater.
- Several laboratories filter the samples, if requested by the client. This may result in sorption of PFAS from the samples and potential cross-contamination, and should be implemented with care.
- After decanting, some laboratories rinse the remaining particulates in the bottle with solvent for the SPE.
- Not all laboratories disclose when samples require special preparation (decanting, centrifuging, or filtering) due to the presence of particulates. Therefore, this would not always be known to the data user.
- Laboratories have different procedures for when particulates clog the SPE cartridge; some labs may re-extract at a dilution, while others may start a new cartridge and attempt to continue with the extraction of the remaining sample.

Laboratories should clearly state whether reported concentrations are dissolved (water only) or “total” PFAS measurements (including sample particulates). The project team will determine whether dissolved or “total” PFAS measurements are appropriate to meet project objectives and confirm with laboratories that correct procedures are in place. Sampling procedures should be designed to gather representative samples to meet project objectives. Some issues to consider in the determination of the need for a total or dissolved PFAS measurement are discussed in this section.

Groundwater

- If minimizing presence of particulates is within the project objectives, use of low-flow groundwater sampling or no-purge samplers should be considered.
- If turbidity is >10 NTU, consider a “total” measurement if sampling groundwater for compliance, delineation, remedial design, or risk assessment. “Total” can be defined as centrifuge, decant, and extract both phases, to report the dissolved concentration and the suspended/solid concentrations either individually or summed in the report.
- Collect samples for TSS analysis to assist in the evaluation of sample data. In lieu of TSS, turbidity measurements can also be helpful in the evaluation.

Drinking Water

- Particulates are not addressed in the drinking water methods.

Surface Water and Wastewater

- Use a “total” measurement if sampling surface water or wastewater for compliance, permitting, remedial design, or risk assessment.
- A “total” measurement may not be required if sampling for a line of evidence in a source area, rather than for a regulation.
- Collect samples for TSS analysis to assist in the evaluation of sample data. In lieu of TSS, turbidity measurements can also be helpful in the evaluation.

For laboratories performing centrifugation and subsequent decanting, it should be noted that it is important that the extracted internal standards are spiked into the aqueous samples prior to centrifugation. It is important to communicate with your laboratory prior to the collection of samples on the approach that will be used.

Biosolids
Biosolids sample preparation methods can vary based on laboratory-specific protocols, the moisture content of the sample, and/or client or regulatory requirements. Because of the variability in sample preparation methods for this matrix, communication with the laboratory prior to submitting samples is essential to understand the laboratory’s options for sample

handling and to ensure that the laboratory will be meeting the project objectives and/or regulatory requirements.

The following preparation methods are possible for biosolids, and may be dependent on the laboratory's standard operating procedures.

- Typical solid sample extraction procedures (e.g., homogenization and solvent extraction) may be used regardless of the moisture content if there are visible or settleable solids. Because regulatory criteria for biosolids are typically established on a mass/unit mass basis (e.g., µg/kg), this may be an approach needed to satisfy regulatory requirements.
- If there are no visible or settleable solids, the laboratory may treat the biosolids sample as an aqueous sample (e.g., passing the sample through a solid phase extraction [SPE] cartridge).
    - When aqueous samples are treated as dissolved PFAS samples, laboratories may centrifuge the samples to separate out any solids or particulates. The aqueous phase would then be decanted and prepared using SPE.
    - Some laboratories may also extract the remaining solid/particulate phase after decanting using a solvent and then use the eluate of this solid sample to elute the PFAS off the SPE cartridge used to extract the aqueous phase, thus combining the aqueous and solid phases into one extract.
    - If samples are not centrifuged, solid particles may become entrained on the SPE cartridge and PFAS from these solid particles may be extracted during the methanol rinse. However, there is also a chance that the solid particles could cause clogging of the SPE cartridge, which would not allow for a complete extraction.

Laboratories may also be able to perform biphasic extraction and report results separately for the aqueous and solid phases.

11.2.1.3 Sample Analysis

Instrument Type–LC/MS/MS

Currently all methods published by the USEPA and DOD for targeted PFAS analysis use liquid chromatography-mass spectrometry-mass spectrometry (LC/MS/MS), which is especially suited for analysis of ionic compounds, such as the PFSAs and PFCAs. Gas chromatography-mass spectrometry (GC/MS) can also be used for PFAS analysis, specifically the neutral and nonionic analytes, such as the fluorotelomer alcohols (FTOHs), perfluoroalkane sulfonamides, and perfluoroalkane sulfonamido ethanols. GC/MS may be appropriate for (ambient) atmospheric samples. PFAS are either directly detected using large-volume injection (Scott et al. 2006) or detected as a derivatized compound that is GC/MS amenable (Langlois et al. 2007). At this time, there is no published GC/MS method and very limited commercial availability for the technique for PFAS analysis.

In contrast, LC/MS/MS analysis of PFAS is widely available. LC/MS/MS is typically operated in multiple reaction monitoring (MRM) mode, which allows for selective monitoring of both the precursor and (potentially) unique daughter ions that are produced upon fragmentation in the mass spectrometer; this allows for specific and selective monitoring for compounds of interest. MRM is performed by specifying the mass-to-charge ratio of the compound of interest for fragmentation within the MS/MS. The precursor mass of the compound of interest undergoes MS/MS fragmentation, followed by monitoring for product ions. Ions arising from that fragmentation are monitored for by the MS/MS, which yields improved specificity and sensitivity.

Standards Preparation and Storage

Certified analytical standards are available from several manufacturers. Products may have variable purity and isomer profiles, which may compromise the accuracy, precision, and reproducibility of data. Certified standards of the highest purity available are standards that can be used for accurate quantitation. Standards manufacturers should provide a certificate of analysis (COA) with each standard, which provides the analyte concentrations and the purity information. Regarding expiration dates, laboratories should have their own policy in place for expiration date determination.

Quantitative standards containing linear and branched isomers are not commercially available for all applicable analytes. Currently, quantitative standards are available for PFOA, PFOS, perfluorononanoic acid (PFNA), perfluorohexane sulfonic acid (PFHxS), perfluorooctane sulfonamide (PFOSA), N-methyl perfluorooctane sulfonamide (NMeFOSA), N-ethyl perfluorooctane sulfonamide (NEtFOSA), 2-(N-methylperfluorooctanesulfonamido) acetic acid (NMeFOSAA), 2-(N-ethylperfluorooctanesulfonamido) acetic acid (N-EtFOSAA), methyl perfluorooctane sulfonamido ethanol (NMeFOSE), and N-ethyl perfluorooctane sulfonamido ethanol (NEtFOSE).

Technical grade standards, or qualitative standards, that contain branched and linear isomers are available for other PFAS, but these standards do not have the accuracy needed for quantitation purposes. USEPA Draft Method 1633 and DOD AFFF01 both require the analysis of technical grade standards to verify which peaks represent the branched isomers for method analytes when these standards are available.

Stock standards of PFAS analytes, internal standards, and surrogate standards supplied in glass ampoules by the manufacturer are acceptable. Manufacturers of the certified analytical standards often provide laboratories storage and shelf-life guidance for stock and working standards. USEPA Methods 533, 537.1, 8327, Draft Method 1633, OTM-45, and DOD AFFF01 contain storage requirements for both reagents and/or standards.

Steps to Help Eliminate Laboratory/Instrument Contamination (Verification of Supplies, Instrument Blanks, Isolator/Delay Columns)

Laboratory and instrument contamination is of particular concern for PFAS, given that the limits of detection are in the ppt range. Additionally, nonpolymer PFAS may be found at trace levels as impurities in some polymer products (3M 1999). PFAS are found in commonly used laboratory items such as PTFE products, solvent lines, and methanol, which could lead to method interferences and elevated baselines in chromatograms if not checked. The evaluation criteria for equipment and standards that is applicable depends on the analytical method used. For instance, USEPA Methods 537.1 and 533 recommend that all of the above items must be "less than 1/3 the MRL (minimum reporting limit) for each method analyte under the conditions of analysis by analyzing laboratory reagent blanks." (USEPA 2020, pg. 7). USEPA Method 533 further specifies that the isotopically labeled analogs of method analytes and isotope performance standards meet this same requirement (USEPA 2019, pg. 7).

Most vendors have a PFAS kit available that replaces as many PFAS-containing components as possible. In addition, the liquid chromatograph can be fitted with an isolator or delay column to separate contamination arising from the solvent delivery systems. This can reduce the contribution of PFAS from the pump apparatus to the analysis and reduce detection limits. Guard columns should be used to protect analytical columns.

Ion Transition Selection (Recommended Transitions for Primary and Confirmation Ions, Including Ratio Criteria)

Quantification by LC/MS/MS may be accomplished using a variety of techniques. For relatively simple matrices such as drinking water, USEPA Method 537.1 quantifies analytes by comparing the product ion of one precursor ion and retention time in samples to calibration standards. For more complex matrices, additional product ions and their ion ratios can be used to distinguish analytes from matrix interference. In an MS/MS system, most analytes can be fractured into more than one ion. By monitoring the area of each ion and comparing the ratio of those area counts, a more definitive identification can be made. This identification allows the analyst to distinguish true target analytes from false positives. This more detailed quantification is not required for drinking water matrices, but it is useful for more complex matrices. USEPA SW-846 Method 8327, USEPA Draft Method 1633, and DOD AFFF01 all require two ion transitions from precursor to characteristic product ions be monitored and documented for each analyte, with the exception of those analytes without a suitable secondary transition (for example, species with nondetectable or low signal secondary transitions, such as PFBA, PFPeA, PFMPA, and PFMBA). These methods determine ion transition ratio criteria by comparison with the analysis of analytical standards and use these ratios to evaluate potential bias in sample results.

Mass Calibration, Calibration Criteria, and Calibration Verification

All LC/MS/MS instruments require mass calibration prior to initial calibration. Mass calibration and mass calibration verification should be performed at setup, after performing maintenance that is required to maintain instrument sensitivity and stability performance, and as needed based on QC indicators, such as calibration verifications, as required by USEPA Draft Method 1633. Mass calibration should be performed according to the manufacturer's instructions. In addition to the manufacturer-specified mass calibration verification, the method also requires the accuracy of the ion masses monitored by the method be verified.

Following mass calibration and mass calibration verification, an initial calibration should be performed and verified. All of the published USEPA methods and the DOD method contain requirements for instrument calibration and calibration verification specific to the PFAS concentrations expected in the media for which the method is applicable. USEPA Method 537.1 uses internal standard quantitation, while USEPA Method 533 and USEPA Draft Method 1633 use isotope dilution and extracted internal standard quantitation. USEPA SW-846 Method 8327 uses external calibration quantitation. Isotope dilution quantitation is recommended for complex matrices. The instrument is required to be calibrated at setup and as needed following QC failures such as initial calibration verification (ICV) or continuing calibration verification (CCV) failure. The lowest calibration point should be a concentration at or below the Minimum Reporting Limit (MRL), Minimum Level (ML), or Limit of Quantitation (LOQ), depending on the method. Most methods require the analysis of a standard at the MRL, ML, or LOQ concentration at least daily to document the instrument's ability to accurately quantitate down to that concentration. In addition, some methods also require a reporting limit check QC sample (for example, LLLCS or LLOQ verification sample) to be included with each sample preparation batch to demonstrate adequate quantitation at the lowest concentration is achievable using the sample preparation techniques required by the method.

Some methods, such as USEPA SW-846 Method 8327, require analysis of an ICV, which is a calibration verification standard prepared from a source separate from the calibration standards and analyzed after each initial calibration and before sample analyses are performed.. CCVs or CVs should be analyzed at the frequency specified in the analytical method. Most USEPA methods require at a minimum CCV/CV to be analyzed prior to sample analysis on days an ICV is not analyzed, after every 10 field samples, and at the end of the analytical sequence. Some methods rotate the concentration of CCVs/CVs to cover the entire calibrated range of the instrument and vary the acceptance criteria depending on the concentration. For example, in USEPA Method 537.1, the calibration acceptance criteria for each analyte are that the lowest calibration point must be within 50–150% of its true value while the other calibration points must be within 70–130% of the true values.

Isotope dilution and extracted internal standard quantitation can correct bias resulting from loss during sample preparation, such as in USEPA Methods 533 and Draft Method 1633. In the case of USEPA SW-846 Method 8327, isotopically labeled analogs are used as surrogates to monitor for loss without being used for recovery-correction of target analyte concentrations. Isotope dilution is a quantitation technique that considers sample matrix effects on each individual PFAS quantitation in the most accurate and precise manner possible. This technique quantifies an analyte of interest against the isotopically labeled analog of that analyte, which is added to the sample prior to the onset of sample preparation. EIS quantitation is the comparable technique used when an isotopically labeled analog of an analyte is not commercially available. Addition of EIS prior to sample preparation helps account for loss of analyte during the preparation process and for bias associated with the instrumentation. Calibration criteria for methods using isotope dilution and EIS quantification schemes can be found USEPA Methods 533 and Draft Method 1633. Methods using isotope dilution should include isotopically labeled analog recovery for each sample and analyte in data reports. Isotopically labeled analog recoveries should be reported, and minimum/maximum isotopically labeled analog recoveries may be required by specific analytical procedures. For instance, USEPA Draft 1633 determines the recovery of these analogs through comparison to the response of analogs typically called non-extracted internal standards (NIS) added to the sample after extraction, prior to analysis. Depending on project DQOs, low isotope recovery may indicate that quantitation was inadequate; the data are then reported as estimated values or not at all.

Instrument Blanks: When Are They Needed, Criteria, and Corrective Actions to Take

Due to the extensive use of PFAS, instrument blanks are critical in determining if the instrument is potentially affecting PFAS concentrations in samples. Some methods, such as USEPA Draft Method 1633, require instrument blanks to be analyzed following the highest calibration standard analyzed, daily prior to sample analysis, after each CCV/CV, and following samples that exceed the calibration range to ensure carryover does not occur. The acceptance criteria for instrument blanks are dependent on the method. For example, USEPA SW-846 Method 8327 requires the concentration of each analyte to be ≤ ½ the LLOQ or < 10% of the sample concentration. USEPA Draft Method 1633 is the only method which states that if instrument blanks indicate contamination following the highest calibration standard, corrective action, such as calibrating with a lower concentration for the highest standard, must be taken and successful analysis of an instrument blank following the highest standard analyzed determines the highest concentration for which carryover does not occur.

Matrix Interferences

Aqueous

Interferences related to the matrix can be caused by the co-extraction of contaminants from the sample. These matrix interferences can have considerable variation from sample to sample. For example, there are problems associated with high total organics content (TOC) in water, which can cause matrix suppression of target analytes and lead to poor recoveries.

Tissue

Interferences related to the matrix can be caused by the co-extraction of bile salts (for example, taurodeoxycholic acid, taurochenodeoxycholic acid, and tauroursodeoxycholic acid) with PFOS from the tissue sample. These bile salts can vary considerably from sample to sample and by species. The use of carbon clean-up steps, such as those required by USEPA Draft Method 1633, helps eliminate these interferences in most extracts; however, when excessive amounts are present in the extract, these steps may only reduce the amount of these bile salts. To address the potential interference, USEPA Draft Method 1633 requires that the chromatographic conditions are adjusted such that these bile salts elute at a retention time beyond 1 minute from the retention time window of PFOS. Since bile salts can be associated with other matrix types (for example surface waters and wastewaters), the method requires this chromatographic separation to be demonstrated with each analytical sequence, regardless of the matrix type of the sample.

11.2.2 Qualitative Techniques

Several techniques employing indirect measurement have been developed that can more comprehensively assess sites for a wider range of PFAS contaminants than in the typical LC/MS/MS or GC/MS/MS methods. These qualitative techniques are not yet standardized through a published USEPA method and range in commercial availability. To date, these techniques have not undergone multilaboratory validation, and tend to be inherently nonquantitative; accordingly, data from these methods may supplement but not replace the results of quantitative methods.

11.2.2.1 Overview of Qualitative Techniques

Because of the large number of PFAS and their varied structural characteristics, a single targeted method on either LC/MS/MS or GC-MS/MS may be unable to quantify all PFAS that may be present in a sample. When the release source is well understood and the types of PFAS present are both known and amenable to regular PFAS analysis methods (for example, LC/MS/MS of ionic PFAS or GC-MS/MS analysis of neutral PFAS), a targeted analytical approach may be sufficient to adequately characterize a release. For releases that are not well understood or consist of multiple sources, alternative ways of measuring PFAS in a more comprehensive but less targeted fashion may be desirable. Additionally, PFAS that are in polymeric form, such as those used in coatings for paper and textiles, are not amenable to LC- and GC-based separation techniques; they may also not be effectively extracted, even with rigorous methods.

Five primary techniques have been developed to characterize unknown PFAS in a sample. These techniques are not multilaboratory validated or promulgated by USEPA. They are described in more detail in the sections below.

- The total oxidizable precursor (TOP) assay measures PFAA precursors.
- Particle-induced gamma-ray emission (PIGE) spectroscopy measures elemental fluorine isolated on a thin surface.
- Adsorbable organic fluorine (AOF) or extractable organic fluorine (EOF), paired with combustion ion chromatography (CIC), measures the organofluorine content of a sample as fluoride on an ion chromatograph.
- High-resolution mass spectrometry techniques, such as quadrupole time-of-flight (qTOF) MS/MS, can tentatively identify PFAS structures through library matching or in-depth data analysis.
- Chemical Ionization Mass Spectrometry (CIMS) technique detects gas-phase PFAS, particularly fluorotelomer alcohols (FTOHs) and other oxygenated PFAS.

11.2.2.2 TOP Assay

Technique Description

The TOP assay converts PFAA precursor compounds to PFAAs through an oxidative digestion. The increase in PFAAs measured after the TOP assay, relative to before, is an estimate of the total concentration of PFAA precursors present in a sample, because not all PFAS present will be subject to quantitation or oxidation, and some will remain as undetected PFAS. The PFAAs generated have perfluoroalkyl chain lengths equal to, or shorter than, the perfluoroalkyl chain lengths present in the precursors (Houtz et al. 2013; Houtz and Sedlak 2012; Weber et al. 2017; Dauchy et al. 2017).

The TOP assay is a technique developed to estimate oxidizable precursors that can transform to PFAA end products that are included in the target analyte list (Houtz et al. 2013; Houtz and Sedlak 2012). A sample is analyzed using conventional LC/MS/MS to determine the baseline levels of PFAAs present in the sample. A separate aliquot of the sample is then exposed to a highly basic persulfate solution and then placed in a sealed container at an elevated temperature (for example, 85°C, in a water bath or other heating device) to thermolyze persulfate into a sulfate radical. At elevated pH, the sulfate radical is scavenged by hydroxide and forms a hydroxyl radical, which then converts the free PFAA precursor compounds to PFAAs. The predominant products (for example, > 95% in control experiments) of the precursors are the perfluoroalkyl carboxylates, whether or not the precursors contain sulfonamido or telomer functionalities. After sufficient time has elapsed to convert all the persulfate, the samples are removed from the heated environment (for example, a water bath), cooled to room temperature, and neutralized prior to LC/MS/MS analysis. The increased concentrations of PFAAs generated after the oxidation step provide an estimate of the concentration of oxidizable PFAA precursors.

The technique can be applied to aqueous (Houtz et al. 2013; Houtz and Sedlak 2012; Houtz et al. 2016; Weber et al. 2017; Dauchy et al. 2017) and solid samples (Houtz et al. 2013). In most cases, samples need to be pretreated prior to oxidation to remove competitive organic compounds. For aqueous samples, dilution may be sufficient, although extraction techniques may be used to further remove matrix effects. Soil samples are extracted prior to persulfate treatment, and the extracts are cleaned with ENVI-Carb prior to treating the evaporated extract. The specific extraction procedure used may affect which PFAA precursors are retained for oxidation. For example, acidic extraction procedures may be required to remove cationic precursor compounds from soils (Barzen-Hanson 2017; Mejia-Avendaño et al. 2017).

Possible Technique Uses

The TOP assay may be used to estimate a total concentration of free PFAA precursors in a sample. In some cases, oxidation can be incomplete (Ventia 2019). The total PFAA precursor or total PFAS concentration is considered conservative for the reasons explained below in Technique Limitations. Because the method depends on a compound containing a perfluoroalkyl group, it is highly specific to PFAS. The chain lengths of the PFAAs generated after oxidation provide an indication of whether the precursors are predominantly short- or long-chained, although the production of a particular Cn (where “n” signifies the number of carbons in the alkyl chain) PFAA is not equivalent to the concentration of PFAA precursors containing the same chain length. However, if significant amounts of PFOA are generated after oxidation, that is an indication that the sample contains a comparable concentration of C8 or longer PFAA precursor compounds.

The TOP assay is the most widely commercially available of the qualitative techniques and is typically accepted as a means of determining PFAS load on remediation media to estimate the replacement cycle, but not for site characterization.

Technique Limitations

As mentioned above, the TOP assay does not differentiate between precursors that contain telomer or sulfonamide functionalities, because all these precursors are chemically oxidized primarily to perfluoroalkyl carboxylates. This is significant because a precursor that would likely form PFOS in the presence of a mixed consortium of aerobic bacteria will convert to PFOA under the conditions of TOP assay. The production of branched perfluoroalkyl carboxylates could be attributed to precursors derived from an ECF-based manufacturing process, but environmental samples may not contain the same distribution of branched and linear isomers as was originally generated from the ECF manufacturing process.

The TOP assay results in a mixture of PFCA products from the conversion of fluorotelomer-based compounds (Houtz and Sedlak 2012). For example, 8:2 FTS was converted to 3% PFNA, 21% PFOA, 27% PFHpA, 19% PFHxA, 12% PFPeA, and 11% PFBA in control experiments. Two limitations of the technique arise because of this effect. First, the production of PFOA, for example, is not equivalent to the C8 precursor concentration, because PFOA can be generated from longer-chain telomer compounds and is only a partial product of C8 telomer products. Second, some shorter-chain PFCA products of telomer compounds are not captured, depending upon the analytical methods used for measurement. For example, only 73% of 6:2 FTS was recovered, from a mass balance standpoint, as PFCA products PFBA and longer in control experiments (Houtz and Sedlak 2012). As a result, the TOP assay may under-quantify short-chain PFAA precursors, including those that are telomer-based. Sulfonamido compounds in control experiments did not exhibit a distribution of products; the Cn precursor forms the Cn PFCA in a 1:1 molar ratio.

Some studies have been published on the effectiveness of the oxidative process of the TOP assay on large molecular weight polymer compounds or newer ether-linked PFAS such as ADONA (Zhang et al. 2019). Because PFAS polymers have shown limited ability to biodegrade (Russell et al. 2008; Russell et al. 2010; Washington et al. 2009) relative to low molecular weight free PFAA precursor compounds (Wang, Szostek, Buck, et al. 2005; Lee, D’eon, and Mabury 2010; Wang et al. 2011; Harding-Marjanovic et al. 2015), the TOP assay may be similarly ineffective at converting PFAS polymers to free PFAAs. The TOP assay cannot be used to measure large molecular weight polymeric PFAS unless they are proven to break down in the assay.

For many samples, the TOP assay requires adjustments in dilution, sample preparation, or reagent dosing to achieve complete conversion of PFAA precursors. Standardized quality guidelines are needed to ensure that TOP assay data reflect full conversion of PFAA precursors.

11.2.2.3 PIGE

PIGE is a nondestructive analytical technique that takes advantage of the unique gamma-ray wavelength emission of fluorine when impacted with a proton ion beam. The technique is not compound-specific, but is able to assess total fluorine content of a variety of materials isolated on a thin surface (0.22 mm) (Ritter et al. 2017). The sample is secured in the instrument and bombarded ex vacuo under a 3.4 MeV beam with an intensity of 10 nA for approximately 180 seconds. Two gamma rays characteristic of the decay of the 19F nucleus (110 keV and 197 keV) are measured and the responses integrated. Quantification is achieved with comparison to fluorine-based calibration standards.

In the published literature, PIGE has been used to demonstrate total organofluorine concentrations in papers and textiles (Ritter et al. 2017; Robel et al. 2017) and in food packaging (Schaider et al. 2017). It has also been used on an experimental basis to evaluate organofluorine concentrations in extracted water and soils, but those results are not yet available in the peer-reviewed literature.

Possible Technique Uses

PIGE is a rapid screening technique to measure fluorine on surfaces. If a sample does not contain significant amounts of fluoride or can be prepared to remove inorganic fluoride, PIGE can become a technique specific for organofluorine; however, it is not specific for PFAS. It is a proven way to measure total fluorine in matrices containing high concentration of fluorinated polymeric material, which is a limitation of both the TOP assay and AOF. It also requires relatively minimal sample preparation to analyze fluorine content in commercial products. Sample preparation of environmental samples for PIGE analysis is likely to require a similar level of sample preparation, along with the limitations of extraction techniques, as the TOP assay or AOF.

Technique Limitations

PIGE is not specific to PFAS and, depending on the preparation, it is also not specific to organofluorine. The polymeric compounds that PIGE has been used to detect in consumer products may not contain perfluoroalkyl groups or may not be capable of breaking down to free PFAS. In addition, PIGE cannot distinguish between organic and inorganic fluorine; therefore, the presence of inorganic fluorine can cause results to be biased high.

PIGE also does not provide any differentiation on PFAS perfluoroalkyl chain length present in a sample. Depending on how the sample is prepared prior to the instrumental analysis, samples may be biased toward measurement of long-chain PFAS, as with the TOP assay and AOF.

Extraction methods for PFAS in environmental samples have not yet been demonstrated for this technique. When using SPE to extract environmental aqueous samples prior to PIGE analysis, cartridges that are suitable to hydrophobic and anionic PFAS may not retain positively charged PFAS of interest. For soil samples, the extraction method also determines the PFAS likely retained. However, by using targeted extraction techniques for PFAS in environmental samples, the method becomes much more specific for PFAS.

The range of operating conditions for PIGE has not been standardized and so far, the technique has been demonstrated with only one academic laboratory.

11.2.2.4 Adsorbable Organic Fluorine with Combustion Ion Chromatography

AOF (Wagner et al. 2013) or EOF (defined in 11.2.2.1) (Miyake, Yamashita, So, et al. 2007; Miyake, Yamashita, Rostkowski, et al. 2007; Yeung et al. 2008) paired with CIC (AOF/CIC or EOF/CIC) are complimentary terms for an analysis for fluorine content of environmental samples. In this application, an aqueous sample is passed through a carbon-based sorbent on which the fluorine-containing organics adhere. A nitrate wash of the sorbent can be included in the process in an attempt to eliminate inorganic fluorine. The effectiveness of the solvent rinse to remove inorganic fluorine is a function of the specific solvent and sorbent used and the concentration of inorganic fluorine present. The carbon sorbent is then combusted at high temperatures that should completely decompose the organics into their elemental constituents. The gaseous stream is passed through deionized water, which is then analyzed for fluorine content (as fluoride) by ion chromatography. In April 2022, USEPA released the Draft Method 1621, Screening Method for the Determination of Adsorbable Organic Fluorine (AOF) in Aqueous Matrices by Combustion Ion Chromatography (USEPA 2022).

The technique has been demonstrated on human blood samples (Miyake, Yamashita, So, et al. 2007; Yeung et al. 2008) and various environmental aqueous samples (Miyake, Yamashita, Rostkowski, et al. 2007; Wagner et al. 2013; Dauchy et al. 2017; Willach, Brauch, and Lange 2016). Presumably, the method could be adapted to other types of matrices to measure organofluorine in soils or biota. The matrices could be extracted for PFAS, the extract resuspended into an aqueous solution that could adhere to the activated carbon, and then analyzed with CIC. As with the TOP assay, the specific extraction procedures would influence whether some or all PFAS are retained and ultimately measured as combusted fluoride product. Alternatively, it is possible that the technique could be used without extraction to directly combust organofluorine-containing products.

Possible Technique Uses

AOF can be used to measure PFAS or other fluorine-containing compounds as an aggregate organofluorine concentration. If the method is available more readily or at a lower cost than LC/MS/MS measurement of PFAS, it can be a screening tool to determine if a significant concentration of fluorine-containing compounds is present in an aqueous sample or other sample from which the organofluorine content can be extracted. A detection limit of 0.77 µg/L fluorine (13 µg/L PFOS equivalent) (Willach, Brauch, and Lange 2016) was reported for one laboratory offering the technique, although the detection limit will vary by amount of sample processed and laboratory conducting the procedure.

Technique Limitations

Like PIGE, AOF is not specific to PFAS. If a sample contains relatively high concentrations of chemical compounds that are not targets of the investigation (for example, fluorine-containing pharmaceuticals), then the organofluorine may be falsely attributed to PFAS content and bias “total PFAS” measurements high.

AOF does not provide any differentiation on PFAS perfluoroalkyl chain length present in a sample. Some short-chain PFAS may be unable to sorb to the activated carbon material that is combusted, but this will depend significantly on laboratory-specific procedures.

Extraction methods for PFAS in commercial products and solid samples, coupled with this technique, have not yet been demonstrated for this technique. A high concentration of inorganic fluoride concentrations may be challenging to remove from some matrices and would result in samples biased high for total organofluorine that was actually attributable to fluoride.

Like PIGE, the range of operating conditions for AOF-CIC has not been standardized. In addition to the limitations mentioned above, some matrices may contain sufficient competitive organics or other materials that coat the activated carbon to prevent complete retention of organofluorine compounds.

11.2.2.5 High-Resolution Mass Spectrometry

Technique Description

Quadrupole time-of-flight mass spectrometry (qTOF/MS) can be used to determine both the chemical formula and structure of unknown PFAS in a sample, but analytical standards are required for unequivocal structural identification.

High-resolution mass spectrometry has been used to tentatively identify the molecular formulas and structures of unknown PFAS (Newton et al. 2017; Moschet et al. 2017; Barzen-Hanson et al. 2017). Similar to targeted PFAS analysis, techniques such as LC or GC are used to separate compounds in a sample so that individual PFAS can be resolved. The mass is measured using a time-of-flight or other high-resolution detector, and the molecular formula is proposed. If an MS-MS technique is used, the fragments of the precursor compound can be used to piece together the structural arrangement of the compound. To identify compounds that are specifically PFAS, versus other organics present in the sample, compounds with negative mass defects (that is, the accurate mass is slightly less than the nominal mass) can be selected. Fluorine is one of the few elements that has a negative mass defect, and the inclusion of multiple fluorines in a PFAS molecule means that net mass defect of the molecule will likely be negative. Compounds that are either 50 or 100 mass units apart also identify homologous series of PFAS separated by one or two CF2 groups. MS libraries of previously identified PFAS exist for targeted matching, although they will not definitively identify an unknown compound.

Possible Technique Uses

Such high-resolution mass spectrometry analyses of PFAS can tentatively identify the structures of unknown PFAS and can also be used, in comparison with analytical standards of known compounds, to semiquantitatively estimate their concentrations. Accurate identification of compounds using high-resolution MS is a time-intensive and expensive process. Therefore, a high motivation for knowing the exact PFAS structure, for instance in differentiating forensically between two different sources, may be the biggest driver of its use for PFAS analysis. High-resolution MS is best suited for media in which unknown PFAS are likely to be present in significant concentrations. When many other non-PFAS are present in the sample, the MS signal of competing compounds will likely obscure the signal of PFAS. Sample preparation steps can inadvertently or intentionally select for certain types of PFAS. As user skill and data interpretation time increase, accurate identification of PFAS is likely to improve.

Technique Limitations

High-resolution mass spectrometry cannot definitively identify the exact structure or formulas of PFAS without comparison to reference materials or analytical standards.

Not all PFAS, even if present in a prepared sample, can or will ionize under the conditions to which the instrument is tuned. A skilled instrument operator may be able to adjust the instrument conditions to match the types of compounds expected.

False positives are much more likely to result using high-resolution MS than with the TOP assay, AOF, or PIGE. Compounds may be mistakenly identified as PFAS, and even when correctly identified, their concentrations may be greatly over- or underestimated when other compounds are used for comparative quantitative purposes.

11.2.2.6 Chemical Ionization Mass Spectrometry

Chemical ionization mass spectrometry (CIMS) can be used to detect gas-phase PFAS, particularly fluorotelomer alcohols (FTOHs), and other oxygenated PFAS.

Although GC/MS is not a common or well-established technique used for PFAS analysis, it is particularly applicable to (ambient) atmospheric samples. Currently, there are no published methods for using GC/MS for PFAS analysis, despite the distinct advantages for certain compound classes (for example, fluoro-telomer alcohols) of using GC/MS directly or after derivatization (chemical reaction to convert analyte of interest to a GC/MS-amenable “derivatized compound”) (Langlois et al. 2007), or using large-volume injection (Scott et al. 2006).

11.3 Data Evaluation

Evaluation of data involves looking at all the factors that indicate whether the data are:

- precise (agreement between results that are supposed to be similar)
- accurate (how close they are to the true concentrations)
- representative (results characterize the site properly)
- comparable (data compare well to other data)
- complete (all the samples and compounds requested were reported, especially for critical samples that represent a point of exposure, such as drinking water)
- sensitive (nondetect data reported with concentrations below required regulatory or risk-based level)

These factors are illustrated in Figure 11-1, and guide users through the process of looking at their data (field collection and laboratory information) with a critical eye.

The USEPA has guidance to aid in evaluating PFAS drinking water data generated in accordance with USEPA 537, *Data Review and Validation Guidelines for Perfluoroalkyl Substances (PFASs) Analyzed Using EPA Method 537*, as well as a technical bulletin to aid in the review of PFAS data generated for all other media, *Per- and Polyfluoroalkyl Substances (PFAS): Reviewing Analytical Methods Data for Environmental Samples*. The USDOD EDQW has published PFAS Data Validation Guidelines, for evaluation of PFAS data generated in accordance with the *DOD/DOE Quality System Manual (QSM) Table B-24* (USDOD 2022). A summary of key points from these data validation guidance documents, and others as noted in the table, has been compiled as Table 11-6, PFAS Analytical Data Usability Table (included as a separate PDF).

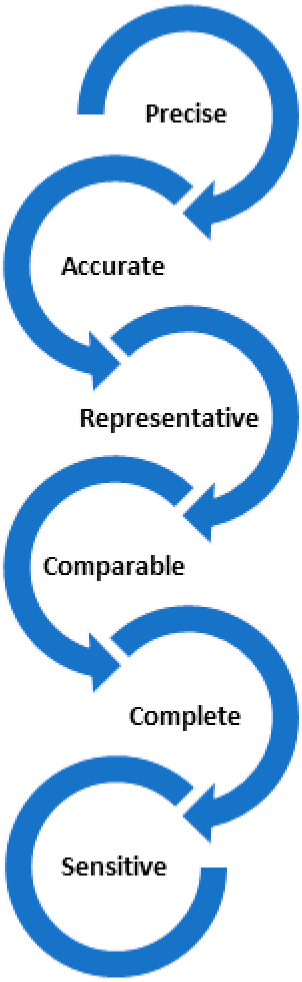


Figure 11-1. Data evaluation factors.

Source: H. Albertus-Benham, Wood Environment & Infrastructure, used with permission.

11.3.1 Pre-sampling Planning

To ensure the usability of the data, communication with the laboratory that is performing the analysis is important. Until there are accepted methodologies for matrices other than drinking water, it is incumbent on the data user to collect information about the methodology to be employed by the laboratory. Figure 11-2 contains laboratory considerations related to data usability in order to plan a sampling program.

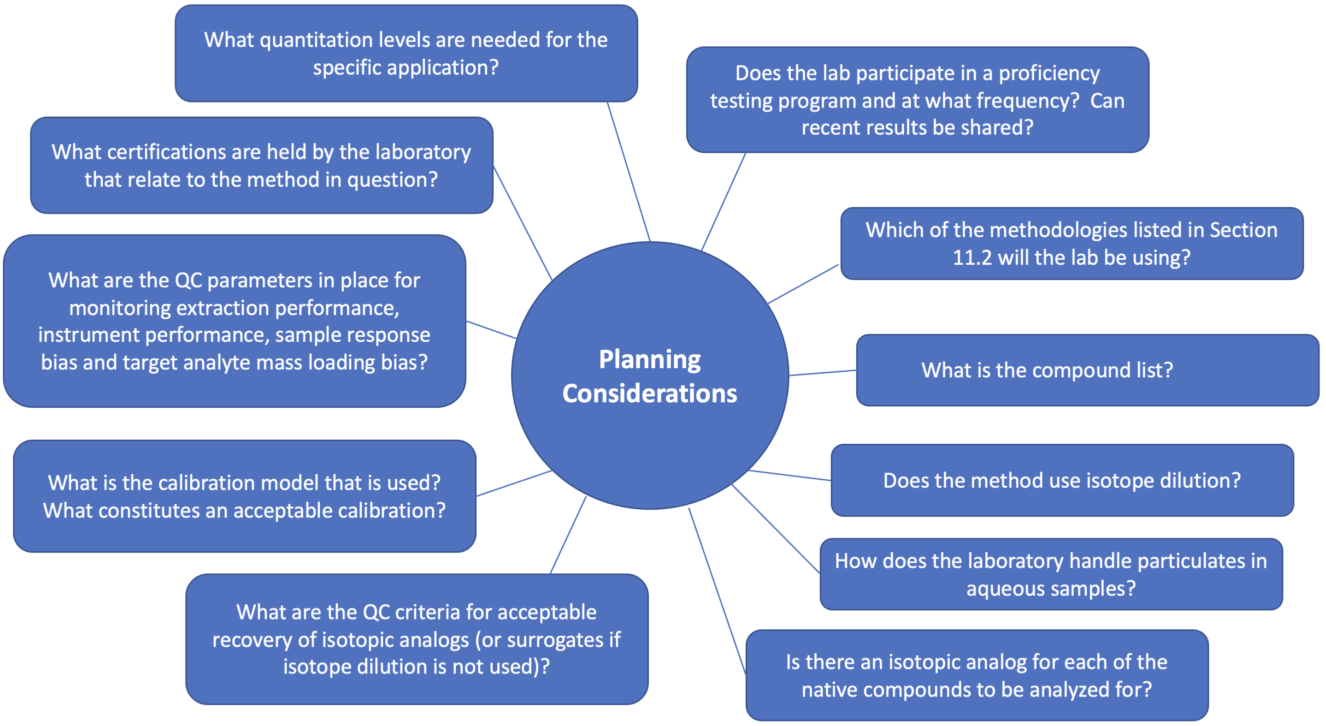


Figure 11-2. Laboratory planning considerations for data usability.

Source: Modified from figure by H. Albertus-Benham, Wood Environment & Infrastructure. Used with permission.

Throughout the rest of Section 11.3, pre-sampling planning will be indicated by these yellow call-outs.

The most important goal of data usability is to ensure that the PFAS data generated are usable to meet the stated data needs and that the user understands any limitations in the use of the data due to potential uncertainty or bias. Overall usability of data is judged by evaluating the quality of the results compared to the data quality objectives (DQO) of the project. Therefore, establishing these project DQOs and communicating them to the field sampling team and the laboratory prior to sample collection and sample analysis is vital to ensuring that the correct methods, correct compounds, and adequate sensitivity are reported for your samples.

11.3.2 Overall Usability of the Data

Three questions are most important in evaluating data: (1) Have the results exceeded a level of concern?, (2) Do these results make sense?, and (3) Are data of acceptable quality? To judge whether results have exceeded a level of concern, the potential bias or uncertainty in the data should be evaluated along with the sensitivity of the results. At a minimum, it is recommended that a report from the laboratory contains a cover letter (or narrative) explaining sample receipt, analytical methods, and any QC deviations plus data sheets for field samples and QC samples (method blanks, laboratory control samples, sample duplicates, matrix spikes), which should also contain results for sample-specific QC (such as internal standard recoveries). Often the most critical data for a project are the non-detects to prove the absence of compounds of concern at specific concentration levels (quantitation limits). Therefore, before evaluating QC associated with your samples, the data should be evaluated to ensure that all compounds required are reported with quantitation limits at or below the project's required sensitivity objective. If this sensitivity is not acceptable, then the data may be of very limited use.

If the compound list reported and quantitation limits are acceptable, then the associated QC results (for example, EIS recoveries, results of blanks, laboratory control sample recoveries, etc.) can be compared to project DQOs to evaluate potential uncertainty in the data. The formal systematic process of this QC evaluation is called data review or validation. The approach to data validation is well documented; for example, see the USEPA National Functional Guidelines (USEPA 2020, USEPA 2020), and beyond the scope of this document; however, evaluation of all of the QC associated with the sampling and analysis of a set of samples will lead to an understanding of the uncertainty in the data.

Some critical QC issues might result in unusable data or concern for project actions. For example, if the data are considered biased low based on low QC results and the sample concentrations are at or near the level of concern or an action level, it may be that the true sample concentration actually exceeded the action level. Conversely, if the sample data are considered biased high based on high QC results and the sample concentrations are near but below the levels of concern or action level, then there is added certainty that the data do not exceed the action levels.

Once the data have been adequately reviewed for accuracy to determine if there are limitations to their use or uncertainties to be considered during use, the results should be evaluated by answering the following questions:

- Do field duplicates, if performed, indicate acceptable precision for the sampling and analysis?
- Do the data from the current sampling event compare well with historical data?
- Do the data make sense from a spatial and temporal point of view?
- Do the data make sense from a spatial point of view from one sampling point to the next across the project area?

This type of review can point out data trends or areas of concern (for example, interferences with project analytes) that could not be elucidated by looking at a single data point and may lead to overall project changes such as a need to increase sampling density to improve data representativeness, correction of procedures for collecting samples to minimize contamination, changes in methods of analysis to achieve project sensitivity requirements, etc. Following this review, the data user can determine whether the data set is complete and sufficient for project decisions and data uses or whether additional samples need to be collected and analyzed.

Evaluating results may lead to overall project changes such as a need to increase sampling density to improve data representativeness, correction of procedures for collecting samples to minimize contamination, changes in methods of analysis to achieve project sensitivity requirements, etc.

11.3.3 Sensitivity

A quantitation limit (QL), or Limit of Quantitation (LOQ) is the limit of accurate quantitation for a specific analyte in a specific sample after any adjustments have been made for sample amount, dilutions, or percent moisture. Typically, the QL or LOQ concentration is selected as the lowest nonzero standard in the calibration curve for each analyte. It considers the sample size, matrix effects, and any dilutions made during the analysis of that particular sample. Because of varying properties between samples, the QL can vary from sample to sample and analyte to analyte. The QL should represent the level at which reliable qualitative and quantitative information is routinely reported (Table 11-3, included in the PFAS Analytical Methods Excel File). When project-specified decision levels or action levels are near the QL, at least one QL check is recommended in all sample batches to demonstrate adequate quantitation at the lowest concentration.

Sensitivity is related to the QL in that sensitivity refers to the capability of a method or instrument to identify a given analyte at a given concentration and reliably quantitate the analyte at that concentration. If a specified analyte is not reported by a laboratory to be in a specified sample, it does not necessarily mean that the chemical is not present; it is an indication that the concentration of the analyte may be below the method sensitivity.

Detected PFAS results between the method detection limit (MDL) and QL (that is, “J” values) can generally be reported if all qualitative identification criteria are achieved. Typical QLs for PFAS are as follows:

- common PFAS analytes in aqueous matrices: 2–8 ng/L (ppt)
- common PFAS analytes in solid matrices: 0.2–2 ng/g (ppb)

Sometimes even though lower QLs were planned for, the laboratory may have to perform dilutions, which causes the QLs to be elevated. Ensure that the dilution performed by the laboratory was reasonable. If there are elevated concentrations of specific target analytes or interferences, then the dilution is likely justified and the presence of elevated QLs may not be an issue if these other target analytes are present at very high levels.

It is imperative that the QLs (and not the MDLs) for each method are evaluated versus the project screening criteria prior to submitting samples to the laboratory. The QLs should be below the project screening criteria to ensure achievement of project objectives.

If a dilution was performed and it is not obvious why (for example, low concentrations or nondetect results for target analytes), then inquire with the laboratory why the dilution was performed. This could happen due to elevated concentrations of non-target compounds but should be documented.

The QLs can also be affected by the sample preparation parameters, the mass of solid sample or volume of aqueous sample used in the extraction, or the final volume of the extracts. If a complex matrix is encountered, the sample sizes may be reduced and/or the extract volumes may be increased, causing the QL to be elevated accordingly.

11.3.4 Target Analyte Lists

Target analyte lists for PFAS will vary by laboratory and regulatory program. The data user should work with the laboratory to ensure that the correct list is being reported, as dictated by the project objectives. In general, Table 11-4 (included in the PFAS Analytical Methods Excel File) includes the common PFAS reported by existing laboratories. The selected list may be dependent upon project objectives, regulatory requirements, as well as the potential source of PFAS contamination (for example, AFFF, landfill, chromium electroplating). Note that a published method may not include analytes important to characterization of a particular matrix, for example, diPAPs for biosolids characterization (Dickman and Aga 2022[2867]).

The data user should work with the laboratory to ensure that the correct list is being reported, as dictated by the project objectives and regulatory compliance.

11.3.5 Linear and Branched Isomers

It is also important to note that PFOS and PFOA (and other PFAS as well) contain a mixture of linear and branched isomers, which can be significant when the laboratory is quantifying these chemicals. Very few standards are available for branched isomers; some are qualitative and some are quantitative. If branched isomers are not included in the sample quantitation by the lab, the resulting concentrations will be underestimated.

In general, all laboratories should be reporting the sum of the linear and branched isomers for PFHxS, PFOS, PFOA, PFNA, PFOSA, NMeFOSE, NEtFOSE, NMeFOSA, NEtFOSA, NMeFOSAA, and NEtFOSAA because these are the PFAS for which both linear and branched analytical standards currently exist. In the absence of a standard that includes branched isomers, only the peak associated with the linear isomer is integrated. As more analytical standards become available, more PFAS should be reported as linear and branched in the future.

Figure 11-3 shows an example of the integration performed correctly and incorrectly. It is the responsibility of the data user to ensure that the laboratory is performing the integration of the target PFAS to include both linear and branched isomers. This requires upfront communication with the laboratory and a possible independent review of the laboratory raw data by a qualified chemist/data user to verify the integrations were properly performed.

Ensure that the contracted laboratory is performing the integration of the target PFAS to include both linear and branched isomers.

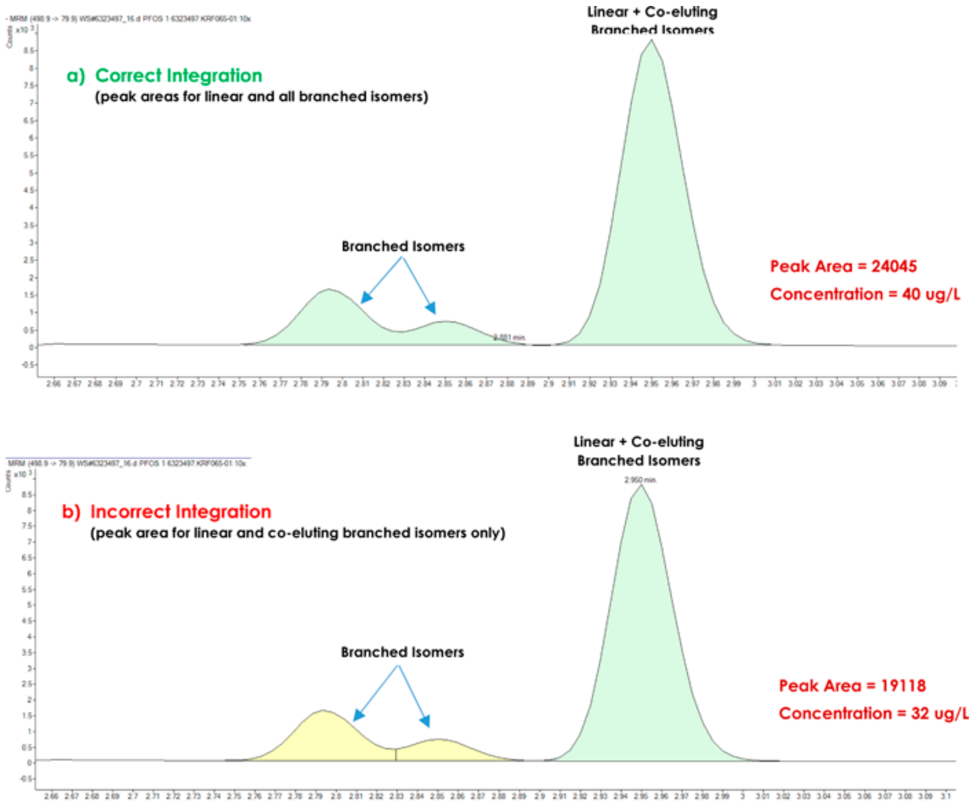


Figure 11-3. LC/MS/MS data illustrating a) complete integration of linear and branched PFOS, and b) partial integration of PFOS. Discrepancies in concentration will depend on the fraction of branched versus linear PFAS present, but in the current example PFOS concentrations in b) were 20% lower than in a).

Source: Bureau Veritas Laboratories, Mississauga, Ontario, Canada. Used with permission.

11.3.6 Isotope Dilution Standard Results and Surrogates

Isotope Dilution Standards

The isotope dilution technique involves quantitation of a compound of interest using a labeled isotope of that very compound. A variety of isotopically labeled analogs (for example, carbon-13 analogs of the compounds of interest) are added to a sample prior to extraction or prior to analysis when extraction is not required. These isotopically labeled analogs are sometimes referred to as extracted internal standards, as defined in the USEPA Draft Method 1633, or isotope dilution analogues, as defined in USEPA Method 533, and function from a data usability standpoint as both an internal standard (used in the calculation of the target compounds) and as a surrogate standard (calculation of the recovery of the standard). Ideally, the number of isotopically labeled analogs used in the isotope dilution technique matches the number of target compounds. Non-extracted internal standards, as defined by USEPA Draft Method 1633, or isotope performance standards, as defined by USEPA Method 533, are also added to the sample or extract immediately preceding analysis, and are used to calculate recovery of the extracted internal standards.

For the isotope dilution methods, quantitation of the target compounds is performed relative to the response of the isotopically labeled analog, which should recover in a manner similar to how the nonlabeled compounds recover. Effectively, the sample data are recovery-corrected for losses that might have occurred during sample processing. The isotope dilution recovery correction procedure greatly improves the accuracy of the analysis and is an improvement over other techniques for the analysis of complex samples for analytes requiring high sensitivity. Chemical standards manufacturers are working to make a wider variety of labeled isotope compounds available to further improve accuracy of the methods for all compounds under investigation (for example, fluorotelomers, precursors, various isomers of carboxylates and sulfonates).

Acceptance criteria or control limits for isotopically labeled analog recoveries are either developed by the laboratory or dictated by the requirements of the project (for example, work plan or QAPP-specified criteria, regulatory criteria, or method criteria). Poor recovery of EIS in complex matrices is common; however, if a project requires ongoing analysis of a problematic matrix, the laboratory should perform method development to improve recovery, if possible (for example, change in cleanup procedures, change in the transition ions monitored, etc.). If EIS recovery is very low (for example, < 10% recovery), nondetects associated with the EIS may be false negatives and may not be useable for project objectives. If EIS recovery is low and ≥10%, there may be an indeterminate bias for the affected PFAS. If EIS recovery is high, there will be no effect on non-detects, but positive results for PFAS may have an indeterminate bias.

In the case where an isotope dilution extract is analyzed and requires re-analysis at a high dilution, the sample extract may need to be refortified with labeled isotope compounds or, if possible, a smaller aliquot of sample may need to be extracted to obtain adequate responses of EISs. In reporting the final data, the isotope recovery results from the initial analysis should not be used to adjust the data from the secondary dilution analysis because these recoveries may be affected by ion suppression or ion enhancement due to the elevated concentrations of target PFAS and therefore may not be reflective of the extraction efficiency or other matrix interferences. The result from this scenario is no longer quantitated from an isotope dilution but is calculated from an internal standard calculation and should be noted as such in the case narrative.

Surrogates in Non-Isotope Dilution Procedures

Method 537.1 uses four surrogates for 18 target compounds, while EPA Method 8327 uses 19 surrogates for 24 target compounds. Injection internal standards are also added to the sample extract immediately preceding analysis. Quantitation of the target compounds and surrogates is performed relative to these injection internal standards. The results from the non-isotope dilution technique report concentrations of the target compounds and recovery results for surrogates, and it is up to the data user to determine the impact (that is, bias) of the extraction and analysis on the sample results because results are not recovery-corrected.

Acceptance criteria or control limits for surrogate recoveries are either developed by the laboratory or dictated by the requirements of the project (for example, work plan or QAPP-specified criteria, regulatory criteria, or method criteria). Poor recovery of surrogates in complex matrices is common; however, if a project requires ongoing analysis of a problematic matrix, the laboratory should perform method development to improve recovery, if possible (for example, change in cleanup procedures, change in the transition ions monitored, etc.). If the recovery for a surrogate is below criteria, compounds associated with this surrogate may be biased low. If surrogate recovery is very low (for example, < 10% recovery), nondetects associated with the surrogate may be false negatives and may not be useable for project objectives. If surrogate recovery is high, there will be no effect on non-detects but positive results for PFAS may be biased high.

11.3.7 Blank Contamination

As a consequence of the extensive use of PFAS, samples that may not contain PFAS can become contaminated if they come into contact with samples or materials containing PFAS. The types of blanks commonly used to evaluate contamination are field-based blanks and lab-based blanks. Field-based blanks include field reagent blank (field blank), source water blank, and equipment rinse blank. Laboratory-based blanks include method blank, lab reagent blank, and instrument blank. Reagent, field, and method blanks are prepared and analyzed using the same procedures as for the field samples. Instrument blanks are analyzed periodically to verify the instrument is clean for analysis of subsequent samples.

The possible sources of contamination that may occur during field collection activities and sample preparation and analysis and the recommended procedures to minimize contamination have been previously addressed in Section 11.1.

The reagent blank is used to evaluate the potential PFAS contamination from the reagent water source used to generate the field-based and laboratory-based blanks. A systematic review of all of the blank results compared to the associated field sample results (the group of samples associated with the field-based and lab-based blanks, or the analytical batch of samples associated with a specific method blank) must be made to determine whether the field sample results are accurate. For example, if the reagent water source used in the field is nondetect for PFAS, but contamination is found in any of the other field-based blanks, this indicates potential contamination of the associated field samples from the sample bottle itself and/or during collection, handling, or transport to the laboratory. However, if a laboratory-based blank is also contaminated, the contamination observed in the field-based blanks may have been due to sample handling at the laboratory.

If the conclusion of this systematic blank data review is that an associated sample result may have been contaminated, then the sample result is considered to be biased high or may be a false positive, depending on the magnitude of the blank contamination compared to the field sample result. A general rule of thumb is that if a sample contains a contaminant within 5x–10x the concentration in the associated blank, the results may be biased high or result in a false positive in the sample (USDOD 2019).

11.3.8 Duplicate Results

Laboratory replicates are two separate aliquots of the same sample prepared at the laboratory and put through the entire sample preparation and analytical procedures. Field duplicates are two separate samples collected at the same location at the same date and time that are prepared and analyzed in the same manner as the sample. Laboratory replicates may be performed in lieu of an LCS duplicate or MSD. It should be noted that sometimes laboratories report the results of laboratory replicates performed on samples that are from a different project (that is, batch QC); if the laboratory replicates reported are not from a sample at the site of interest, then these results should not be used in the evaluation of sample data.

During data evaluation, the relative percent difference of each detected analyte versus the acceptance limits should be reviewed. The acceptance limits should be provided within the laboratory report and are either regulatory- or method-specific. When both results are < 2x the QL, the potential uncertainty increases and therefore the acceptance criteria may need to be adjusted.

Review regulatory or method-specific acceptance limits with the laboratory, whether from a QAPP or laboratory-generated.

- If both results are < 2x the QL, relative percent difference criteria can be doubled.
- If one result is detected and one result is not detected, then the evaluation will depend on whether the detected result is > 2x the QL or not. If one result is > 2x the QL and the other result is nondetect, then the variability is considered unacceptable and there may be potential uncertainty in the results for this sample.

Variability in laboratory replicate and field duplicate analyses could be from the sampling process, possibly due to an inefficient homogenization procedure in the field. It could also be from the laboratory aliquoting process, or it could be due to heterogeneity in the sample matrix. The effect on project objectives will depend on the screening criteria and how far above or below these criteria the results are. If the results are close to the criteria with significant variability, this may require collection of more samples to better represent the location. If results are significantly above or below the screening criteria with high variability, it may not adversely affect the ultimate decision-making process.

11.3.9 Acid Versus Anion Form of PFAAs

The data user should be aware of the form of PFAS the laboratory is reporting when comparing to project screening criteria. PFAS are typically formulated as acids, but they are present in the environment and in humans in the anionic form. The differences in names used are the result of the different names for the acid form and the anion form of the chemical (see also Section 2.2.3.1). For example, when perfluorobutanoic acid (PFBA) disassociates and loses its hydrogen in water, it becomes the anionic form (perfluorobutanoate). This becomes more important when looking at physical and chemical properties of these chemicals, because whether they exist as an acid, an anion, or a salt (cation) will affect how they behave in the environment. Typically, laboratories are reporting the acid form of the perfluorocarboxylic acids and perfluorosulfonic acids.

Some target PFAS, such as PFHxS and PFOS, are not available as acids, but rather as their corresponding potassium or sodium salts (K^+ or Na^+). These salts are acceptable starting materials for the stock standards, provided the measured mass is corrected for the salt content according to the equation below. Note that this correction will result in a minimal change to the mass of the acid, but still should be performed for consistency and comparability with other results to ensure the data user that the correct form of PFAS is represented in the final concentration.

$$mass_{acid} = measured\ mass_{salt} * (MW_{acid}/MW_{salt})$$

MW_{acid} = molecular weight of PFAA

MW_{salt} = molecular weight of purchased salt

CAS numbers will change depending on if the acid, anion, or salt form of the PFAS is reported (Table 11-7).

Table 11-7. Example of CAS number differences between acid and anion

Chemical	CAS number
PFOA: Perfluorooctanoate (anion)	45285-51-6
PFOA: Perfluorooctanoic acid (acid)	335-67-1

11.4 Source Identification

As discussed in Section 10.5 Source Identification, one area of focus for PFAS investigations has been environmental forensics, specifically source identification. With so many industrial processes and transport pathways from which PFAS contamination can originate, attributing the occurrence of one or more PFAS to a particular source is of growing interest.

Source identification relies on the compilation of multiple lines of evidence from analytical data and site information, and the use of uni- and multivariate statistical analyses. Analytical lines of evidence include:

- Extended Target Lists
- Linear/Branched Speciation
- Non-Target Analysis (NTA)

These methods are briefly described in this section.

11.4.1 Extended Target Lists

Many commercial laboratories now analyze for more than 40 individual PFAS and some of these compounds may be indicative of a particular product or industrial process. Analyzing samples taken from or near these possible sources and comparing the profiles of those results to the area of concern, also known as chemical fingerprinting, may provide a demonstration of comparability.

11.4.2 Linear/Branched Speciation

The separate reporting of branched and linear PFAS can provide some indication of the process used to synthesize the PFAS detected. Electrochemical fluorination (ECF) produces a larger number of branched isomers than fluorotelomerization, which may be useful in differentiating sources (Benskin, DeSilva, and Martin 2010). This is not default laboratory reporting and needs to be arranged in advance to confirm availability and method details. However, due to isomer-specific differences in instrument response, and fate, transport and organism uptake/depuration, the use of speciated data for any inference more than presence/absence of a manufacturing source type is challenging.

11.4.3 Nontargeted Analysis (NTA)

The ability to identify compounds not targeted for measurement by existing methods is an important need. Nontargeted analyses are critical to being able to identify these compounds. With nontargeted analyses, chromatography (liquid and gas) is combined with high resolution mass spectrometry and multiple ionization techniques to determine atomic molecular weight and associated fragments. These results can be compared to databases for tentative identification (Liu et al. 2019). Further spectral interpretation may result in structural identification. This is particularly useful where no chemical standards exist.

Nontargeted analysis includes high-resolution mass spectrometry and suspect screening and is discussed in more detail below.

11.4.3.1 High-Resolution Mass Spectrometry for Nontargeted Analysis

Although not widely commercially available, recent source research has focused on the use of high-resolution mass spectrometry (HRMS) for more comprehensive qualitative determination and fingerprinting for source attribution.

Many PFAS exist with no certified reference standard to make an initial calibration plot. As such, nontarget PFAS may be present in samples that will not be identified or reported on a standard target analyte list, unless requested. HRMS is emerging as a means for discovery and reporting of nontarget PFAS where each unknown peak may be tentatively identified and quantified at estimated concentrations. Nontarget analyses can be reported by the identification of fragmented organic molecular ions (m/z) that are matched to an analytical reference library. The reporting includes detection of homologous series with or without the presence of nonfluorinated functional groups that create mass defects. Mass defect is the difference between the nominal and exact mass of an atom, which allows prediction of molecular formulas and is the key advantage to using HRMS for nontargeted analysis. Liu et al. (2019) categorized PFAS into the main classes of per/polyfluoroalkyl carboxylic acids, per/polyfluoroalkyl sulfonic acids, fluorotelomers and per/polyfluoroalkyl sulfonamides, per/polyfluoroalkyl phosphates, per/polyfluoroalkyl alcohols, per/poly-fluoroalkylamides, per/polyfluoroalkyl sulfates and N-per/polyfluoroalkyls; tables are available on the NORMAN Suspect List Exchange (https://www.norman-network.com/?q=node/236). Charbonnet et al. (2022) defined the basic homologue series by CnF2n+1, where n > 2 with isomeric PFAS of the same chemical formula differentiated as structural isomers that may be linear, branched in the perfluoroalkyl tail or the head group, or have varying functional groups that could create mass defect.

As evidenced by SERDP-ESTCP funded projects listed below, the development of mass spectral libraries to match non-targeted analytes to source profiles is part of the ongoing research. NTA uses HRMS such as time-of-flight (TOF), ion-trap, or Fourier transform ion cyclotron resonance (FT-ICR) to generate high resolution accurate mass data. As extensive data sets are generated using HRMS, informed data filtering approaches are used to filter the data specific to PFAS related analytes. The data are first screened against previously generated suspect screening libraries that contain chromatographic/spectrometric information for PFAS characteristic to sources such as AFFF formulation, industrial process, and/or manufactured products. Then, mass spectrometry-specific data analyses, such as Kendrick mass defect plots, and general uni- and multivariate statistical analyses, are used to attempt source identification based on the presence/relative abundance of PFAS identified against the suspect screening libraries and other information (Benotti et al. 2020; Charbonnet et al. 2021).

Secondary Sources

SERDP PFAS Novel Methods for PFAS Source Tracking and Allocations

https://www.serdp-estcp.org/News-and-Events/Blog/Novel-Methods-for-PFAS-Source-Tracking-and-Allocations

ER20–1375 Comprehensive Forensic Approach for Source Allocation of Poly- and Perfluoroalkyl Substances – Chris Higgins, Colorado School of Mines

ER20–1121 Establishing an Approach to PFAS Forensics and a PFAS Source Materials Forensic Library – Mark Benotti, NewFields Government Services

ER20–1205 Machine Learning Pattern Recognition for Forensic Analysis of Detected Per- and Polyfluoroalkyl Substances in Environmental Samples – Tohren Kibbey, University of Oklahoma

ER20–1265 Ultrahigh-Resolution Fourier-Transform Ion Cyclotron Resonance Mass Spectrometry for Fingerprinting, Source Tracking, and Allocation of Per- and Polyfluoroalkyl Substances (PFAS) – Jens Blotevogel, Colorado State University

ER20–1056 Improving Access and Utility of Analytical Data for the Confident Discovery, Identification, and Source-Attribution of PFAS in Environmental Matrices – Benjamin Place, NIST, Department of Commerce

Updated September 2023.

12 Treatment Technologies

The PFAS Team developed a Treatment Technologies training module video with content related to this section. Treatment technologies for PFAS in environmental media are still evolving and it is prudent to use caution in implementing long-term remedies. Selection of remedial actions should prioritize protection of drinking water sources and human health, with consideration of other objectives (such as reducing risk to ecological receptors and environmental resources, liability, source area mass, mass flux, generation of PFAAs from precursors). At some sites, it might be reasonable to take short-term site actions that address impacted or threatened receptors with the intent of applying more robust and cost-effective technologies as these are developed.

The treatment technologies described in this section are organized into three categories by degree of development and implementation: field-implemented technologies, limited application technologies, and developing technologies. The criteria for each category are further described below.

12.1 Overview

Treatment technologies exploit a contaminant’s chemical and physical properties to immobilize, separate and concentrate, or destroy the contaminant. The physical and chemical properties of PFAS make many treatment technologies ineffective, including those that rely on contaminant volatilization (for example, air stripping, soil vapor extraction) or bioremediation (for example, biosparging, biostimulation, bioaugmentation). Even technologies such as thermal treatment and chemical oxidation may not be completely effective at treating PFAS, and multiple treatment technologies may be needed for each treatment scenario to address the mixture of different PFAS that may be present.

Treatment technologies can be employed either ex situ or in situ. For example, when groundwater is extracted via pumping from wells and treated, this would be considered an ex situ approach. In contrast, when treatment materials are injected into the subsurface to separate, destroy, or immobilize contaminants in groundwater under the surface, this would be considered an in situ approach. Many existing treatment technologies have generally been shown to be inadequate; therefore, the unique chemical properties of PFAS often require new technologies or innovative combinations of existing technologies.

A range of technologies exists for treatment of either liquids or solids that may be performed either in situ or ex situ. However, field-implemented technologies for treating PFAS in liquids are mostly limited to ex situ technologies.

Field-implemented full-scale treatment of PFAS-impacted liquids or solids is limited to sequestration technologies that remove or bind PFAS but do not destroy them. Sorption using granular activated carbon (GAC) and ion exchange (IX) media has been proven effective at full scale (see Table 12-1 Treatment Methods Table Excel File). Destruction and mineralization technologies, including bioremediation, chemical oxidation, chemical reduction, and thermal technologies, are being tested. This section discusses treatment technologies for liquids (waters, leachates, or other liquid wastes) and solids (soil, sediment, or other solid wastes).

The treatment technologies described in this section are organized by the degree of development and implementation documented in practice or in peer-reviewed literature, regulatory acceptance, and a consensus process. A consensus for the ranking of each technology is determined by the best professional judgment of members of the ITRC PFAS team after evaluating the current information and considering input from other external parties during regular reviews of the document. The three levels used in this discussion are field-implemented technologies, limited application technologies, and developing technologies.

Although categorized in this way for this document, the state of development and application of treatment technologies is a continuum that is ever-changing and evolving quickly. Technologies may progress through these categories between revisions of this guidance document. Most important is that by categorizing, ITRC neither endorses nor repudiates any technology or its proponents regardless of its state of development. Each technology should be evaluated independently to determine the applicability of the technology for the site conditions and desired treatment objectives. The three categories are:

1) **Field-implemented technologies** –Technologies that have been demonstrated at multiple sites, under diverse conditions, by multiple practitioners, are commercially available, and are well documented in practice or peer-reviewed literature. Field-implemented technologies have been demonstrated to meet site-specific PFAS treatment objectives, at the intended final application scale, and are widely accepted in the regulatory and scientific community.

2) **Limited-application technologies** –Technologies that have been implemented on a limited number of sites, by a limited number of practitioners, either at full-scale or field pilot-scale. For this document, full-scale is defined as operation of a fully capable system, intended to entirely address the appropriate aspects of the remedial action objectives (RAOs) for the treated media, and which is not intended to be expanded or supplemented in the future to achieve those final project goals. Field pilot-scale refers to a demonstration project intended to prove the effectiveness of the treatment technology in the field, under site conditions. While these projects may not address the RAOs explicitly or completely, these demonstration projects typically involve continuous operation over months of activity, with robust analytical monitoring, and published results in the peer-reviewed literature. Limited application technologies are supported by a growing body of evidence that they are effective at treating PFAS, but differ from full-scale implemented solutions in that there may not yet be a large body of evidence or broad consensus in the scientific community, including peer-reviewed literature, that the technology meets the criteria for a field-implemented technology. Limited-application technologies for liquids and solids are contained in the Table 12-1 Treatment Methods Table Excel File and discussed in Sections 12.6 and 12.7.

3) **Developing technologies** –Technologies that have been researched at the laboratory or bench scale. Often, the results from developing technologies are reported by only one group (for example, one university, practitioner, or vendor) or lack detailed independent verification of the treatment effectiveness or mechanisms. Among a wide array of experimental technologies under development, only developing technologies that show promise and have some level of publicly available documentation demonstrating effectiveness are included in this guidance document.

The technology evaluations presented herein provide information on the effectiveness of each treatment technology. This information varies widely among technologies and the data provided are based on the reported test conditions and results. Ultimately, the feasibility of a technology to meet applicable regulatory guidance values and standards often depends on site-specific conditions.

As detailed in Section 8.2.2.4, in the United States, the regulatory standards for PFAS treatment are primarily driven by drinking water mitigation and focused on a small subset of PFAS. PFOS, PFOA, PFBS, and HFPO-DA are the only compounds with federal health advisories (USEPA 2022), and most regulatory discharge criteria for PFAS focus on these compounds. In 2023, USEPA proposed the National Primary Drinking Water Regulations (NPDWRs) containing MCL and MCLG values that are currently under public review (USEPA 2023). Some states have guidelines, and several have regulatory criteria for additional PFAS, but precursor and short-chain PFAS are generally not considered in regulations or guidance, although that is beginning to change. The technology evaluation information presented here provides data about all PFAS tested for a given technology. This information varies widely among technologies. Additional information on regulations is provided in Section 8 and the PFAS Regulatory Programs Summary Excel File.

12.1.1 Factors Affecting Technology Selection

Selection of a remedy, with confidence that treatment targets can be achieved, depends on several key factors, including the ability to reliably define the nature and extent of contamination, the availability of proven treatment technologies, and the capacity and tools to measure progress and compliance with desired regulatory criteria. A well-prepared conceptual site model (CSM) requires adequate information and is also fundamental to understanding and presenting the rationale and justification for the selected remedy. Additional information on CSMs is provided in Section 2.6, Section 9, and Section 10.

Moreover, proven treatment technologies are limited in capacity and demonstrated ability to meet chosen treatment targets. The comprehensive discussions contained herein reveal many questions and uncertainties that must be addressed.

As an example, factors affecting PFAS remedy selection can include:

- **characteristics of PFAS.** The wide-ranging chemical and physical characteristics of PFAS affect the treatment effectiveness. Key factors include recalcitrance with respect to common technologies due to the strength of the carbon-fluorine bond, ionic state (anionic, cationic, and zwitterionic), types of ionic groups (sulfonate or carboxylate), lipo- and hydrophobicity, chain length and branching, partitioning coefficients, phase behavior, volatility, solubility, acidity, total PFAS mass, and total concentration.
- **changes in PFAS properties**. Naturally occurring processes or remedial actions for other (commingled) contaminants, such as chlorinated solvents and petroleum hydrocarbons, can affect PFAS distribution and mobility in groundwater (McGuire et al. 2014). Example changes include:
    - The alkyl functional group of some PFAA precursors may be more readily subject to chemical or biological transformation than the fully fluorinated aliphatic chain (PFAAs).
    - Partial degradation of the carbon-carbon bonds in the aliphatic chain reported for some chemical remedies generates short-chain PFAS, which may be more mobile (Guelfo and Higgins 2013).
    - Modifications in aquifer properties (for example, redox or pH) during remediation of commingled contaminants results in a conversion of some precursors to the more stable and mobile PFCAs (McKenzie et al. 2015; McKenzie et al. 2016).
- **co-contaminants, organic matter, and geochemistry.** The presence of co-contaminants, total organic carbon, natural organic matter, minerals, and anions can significantly affect remediation. Some technologies that are designed and implemented to treat PFAS co-contaminants may transform perfluoroalkyl acid (PFAA) precursors into more stable perfluorocarboxylic acids (PFCAs) (McKenzie et al. 2015).
- **community acceptance.** Stakeholders, including community members, are often faced with trade-offs in terms of cost, level of cleanup, and residual contamination as part of remediation efforts.

An additional element of technology selection relates to the optimal conditions under which a specific technology should be considered, as documented in the literature. Not all technologies have been demonstrated as suitable or effective under multiple treatment circumstances. For example, although sorption technologies, such as granular activated carbon or ion exchange media, have been documented in the literature as being both technically effective and generally cost-effective in treating high volume, low concentration liquids, such as drinking water, they are less well suited for low volume, high concentration liquids such as thermal system condensate, ion exchange regeneration fluids, fractionated (for example, reconstituted) foam, or landfill leachate. Conversely, several destructive technologies, such as electrochemical oxidation, nonthermal plasma, hydrothermal alkaline treatment, and supercritical water oxidation, have been shown to be effective for treatment of high concentration, low volume liquids, but may be less suitable for high volume, low concentration liquids. See Section 12.1.4 for considerations for specific environmental media.

For those directly engaged in assessing the suitability of PFAS treatment technologies, a structured process for systematic evaluation is currently under development via a Strategic Environmental Research and Development (SERDP)-funded project (ER18-1633). The project focuses on five lines of evidence to evaluate technology performance and will provide resources to identify relevant information and data gaps and address key questions necessary for that assessment. Additional information is provided in Section 12.9.

12.1.2 Tiered Remedial Approach

Along with the factors affecting technology selection (Section 12.1.1), practitioners should also consider the use of a tiered remedial approach to mitigate the risks posed by PFAS. This may include prioritizing protection of known human receptors from exposure to drinking water contaminated by PFAS by using point of entry (POE) or point of use (POU) treatment systems or connecting residents to public water supplies. Reducing the potential risk to human and/or ecological receptors may require upgrades to wastewater treatment plants; however, large-scale retrofits of wastewater treatment plants for PFAS have not been widely enacted at this time. Once these actions are taken to control risk and exposure, the source(s) of the PFAS contamination can be addressed using the appropriate remedial technology. Cutting off sources and controlling ongoing contaminant flux will influence whether PFAS plumes becoming stable or shrink. Once sources and pathways to receptors are controlled, addressing the pathways of contaminant migration (for example, groundwater plumes, stormwater drainage networks, surface water) becomes the final aspect of the tiered approach. A similar approach for site characterization is described in Section 10.2.

12.1.3 Section Organization

The information presented in the following sections reflects the availability of performance results published, presented, or otherwise publicly available. Those technologies that have been implemented in the field at multiple sites, by multiple parties, and have peer-reviewed or practical documentation of performance are discussed in Section 12.2 and Section 12.3. Projects funded by SERDP and the Water Research Foundation (WRF) are also highlighted. This section discusses the following key elements for each of these field-implemented technologies:

- *treatment description*–background and development of technology
- *treatment mechanism*–separation, sorption, or destruction
- *state of development*–applications and degree of commercial availability
- *effectiveness*–documented treatment effectiveness on PFAS and common co-contaminants along with water quality considerations and pretreatment need and options
- *design/operating considerations* –critical or unique operational or design needs
- *sustainability*–footprint, community enhancement, and cost.

Treatment case studies are presented in Section 15.2.

12.1.4 Considerations for Specific Environmental Media

12.1.4.1 Drinking Water

Public-serving system components are often required to be certified through NSF 61 (https://www.nsf.org), which certifies that they are acceptable for potable water use. Treatment for PFAS in these systems typically uses adsorbents such as GAC (Section 12.2.1.1), IX (Section 12.2.1.2), or RO (Section 12.2.2).

Remedial actions for PFAS-impacted drinking water from private wells and other nondistributed sources can include providing alternative drinking water supplies, such as bottled water, new nonimpacted source wells or surface water, point of entry (POE) treatment (also referred to as POET), and point of use (POU) treatment. POE treats water as it enters a home or building (for example, immediately after a pressure tank for a private well system) and POU treats water at one or more specific locations (for example, at a kitchen faucet where water is typically directly ingested or used for cooking). POE systems provide “whole supply” treatment while POU provides selected usage point treatment.

NSF International has incorporated PFOA and PFOS into two standards – NSF/ANSI 53 for adsorption systems and NSF/ANSI 58 for reverse osmosis systems – to verify the ability of a water treatment device to reduce PFOA and PFOS to achieve the USEPA health advisory levels of 70 ng/L (NSF 2021; NSF 2019). This method does not evaluate the removal of other PFAS that also may adversely impact water supplies. Systems with this certification are mainly small-scale POU systems such as sink faucet filters, refrigerator water filters, and pour-through filters. It should be recognized that although this certification exists, it is not required. This means that other POU systems as well as POE systems (larger wellhead or large public-serving systems) may not be certified under NSF/ANSI 53 or NSF/ANSI 58 but may be acceptable treatment of PFOA and PFOS.

12.1.4.2 Landfill Leachate

Currently, a majority of landfill leachate is treated for conventional constituents by directly discharging or hauling the leachate to publicly owned treatment works (POTWs). POTWs have been designed to remove these conventional constituents (for example, organics and nutrients), but these treatment systems are not effective at removing PFAS. A relatively small percentage of landfills perform pretreatment to address conventional parameters (for example, BOD, COD, TSS, ammonia-N) prior to discharging to POTWs or perform leachate treatment on-site and discharge the treated effluent under National Pollutant Discharge Elimination System (NPDES) permits. There are currently very few landfills that treat or pretreat leachate specifically to remove PFAS, but this may change as national and state surface water and/or pretreatment regulations are developed.

Wei, Xu, and Zhao (2019) presented a comprehensive review of the state of the science on PFAS treatment technologies for landfill leachate. They noted that various technologies have been widely tested for treating PFAS in drinking water or groundwater, but knowledge is limited on the treatability of PFAS in landfill leachate and the effects of the complex leachate matrix. Leachate contains many competing organic and inorganic constituents, and this complex matrix creates significant challenges when choosing a treatment technology for PFAS removal. Oftentimes, pretreatment of the leachate may be required before applying common PFAS sorption technologies such as GAC or ion exchange resins. If pretreatment is not performed to remove these competing compounds, the sorptive treatment media will foul quickly, which may result in operationally complex and/or expensive systems to treat landfill leachate for PFAS using these traditional technologies. Additional information on integrated remedial solutions is presented in Section 12.8.

Destructive technologies such as plasma, advanced oxidation, reduction, photochemical processes, and sonolysis are largely unproven at present on landfill leachate, and their effectiveness is expected to be reduced when used for treating leachate due to the severe water matrix effect (Wei, Xu, and Zhao 2019). In addition, these technologies have typically not been as effective when scaled up from laboratory studies to the field. Supercritical water oxidation (SCWO) destruction of landfill leachate containing PFAS has been demonstrated but is not well documented in peer-reviewed literature. More information about SCWO is included in Section 12.6.3.12.

Filtration systems such as RO have been proven effective as a separation technology for leachate for a wide range of constituents, including PFAS, but can generate a significant fraction of concentrated residuals that requires management by other disposal/treatment technologies. Foam fractionation shows promise in recent studies for selectively separating large percentages of PFAS from leachate (particularly the longer chain PFAS) while generating manageable fractions of high concentration residuals at a much smaller volume relative to RO reject (Burns et al. 2022; McCleaf, Kjellren, and Ahrens 2021; Robey et al. 2020; Smith et al. 2022).

Overall, further research is needed to develop and demonstrate cost-effective treatments for landfill leachate PFAS removal that are effective at field scale.

12.1.4.3 Biosolids

Biosolids generated by wastewater treatment plants have been historically managed through land application, use or disposal at landfills, or incineration. The regulatory landscape for management of biosolids is evolving, and some states have started to require testing, prohibit land application if concentrations of certain PFAS are greater than specific levels, or have implemented bans on land application. Current regulations and guidance are discussed in Section 8 and in the PFAS Regulatory Programs Summary Excel File.

Incineration is a topic of current study to better understand the fate of PFAS due to possible incomplete combustion and byproduct generation (USEPA 2020) and is covered in more detail in Section 12.4.

Additional information on biosolids is presented in the ITRC factsheet for Biosolids and Per- and Polyfluoroalkyl Substances (PFAS) (/fact-sheets/) and Section 2.6.4.

12.2 Field-Implemented Liquids Treatment Technologies

These technologies have been implemented in the field by multiple parties at multiple sites and the results have been well-documented in practice or peer-reviewed literature. The liquid treatment technologies in this section may be applied to a variety of PFAS-impacted media, including drinking water (regardless of source), surface water, groundwater, wastewater, stormwater, or landfill leachate. Not all technologies would be appropriate for all applications. Site-specific evaluation is necessary to identify the best technology alternative for a given liquid, system size, treatment goal, and residual media management scenario.

12.2.1 Sorption Technologies

Sorption technologies have been used for both ex situ and in situ water treatment applications. Multiple sorption media types may be used in series for ex situ applications to optimize overall concentration reduction and removal capacity. Adsorption and ion exchange (IX) are two “sorption” mechanisms by which PFAS can be removed from water. Adsorption is a physical mass transfer process that uses Van der Waals and/or other weak ionic forces to bind the entire PFAS molecule to the surface areas of the adsorptive media. Ion exchange is the exchange of ions of the same charge. Ion exchange targets and binds to the hydrophilic ionized or functional end of the molecule (for example, the sulfonate in PFOS) while releasing an equivalent amount of an innocuous ion (for example, chloride) into the treated water. This technology is generally considered more applicable to high volume, low concentration liquids than low volume, high concentration liquids.

Several influent water parameters can therefore be expected to impact the sorption efficiency for a specific PFAS. These include pH, ionic strength, the nature and concentrations of organic co-contaminants present (including naturally occurring organic matter [NOM]), competing inorganic ions normally present (for example, sulfate, nitrate, bicarbonate, and chloride), and any suspended solids, potentially precipitating impurities (for example, iron, manganese, calcium carbonate), or biological growth that can foul and degrade the performance of the media. Pretreatment steps may be necessary to optimize the performance of such media, including coagulation, precipitation, filtration, pH adjustment, or oxidant removal. Ion exchange media used for PFAS removal from water use both the adsorption and ion exchange mechanisms. The use of two or more different media in series can be considered if the expected increase in overall removal efficiency can be used to justify the increased equipment cost.

Life cycle cost assessments can be used to compare the long-term cost-performance benefits of various sorption media types. Spent media management can be an important consideration when selecting a treatment technology. Common options for spent media management are off-site disposal by thermal destruction (via commercial incineration or cement kilns), reactivation/regeneration for reuse (which may require management of additional waste streams), and landfilling. Information on specific management considerations for spent media are discussed in the respective sections below.

Incineration and thermal reactivation/regeneration offer the possibility of destruction of PFAS waste streams, though incineration has received recent attention due to possible incomplete combustion and by-product generation and is the topic of current study to better understand the fate of PFAS. Incineration is discussed in Section 12.4.

Related Past, Ongoing, and Recent Research Funded by SERDP (ER) and Water Research Foundation (WRF)

- ER18-1395 Electrically Assisted Sorption and Desorption of PFASs
- ER18-1417 Molecular Design of Effective and Versatile Adsorbents for Ex Situ Treatment of AFFF-Impacted Groundwater
- ER18-1052 Remediation of PFAS Contaminated Groundwater Using Cationic Hydrophobic Polymers as Ultra-High Affinity Sorbents
- ER18-1306 Combined In Situ/Ex Situ Treatment Train for Remediation of Per- and Polyfluoroalkyl Substance (PFAS) Contaminated Groundwater
- ER18-5015 Removal and Destruction of PFAS and Co-contaminants from Groundwater via Groundwater Extraction and Treatment with Ion-Exchange Media, and On-Site Regeneration, Distillation, and Plasma Destruction
- ER18-B3-5053 Evaluation and Life Cycle Comparison of Ex-Situ Treatment Technologies for Poly- and Perfluoroalkyl Substances in Groundwater
- WRF 4913 Investigation of Treatment Alternatives for Short-Chain PFAS
- ER21-1191 Determination of Thermal Degradation Products and Residuals of Per- and Polyfluoroalkyl Substances-Laden Sorbent Materials in Gas and Condensed Phases
- ER21-1238 Sustainable PFAS Treatment Using Layered Double Hydroxide (LDH) Sorbents
- ER20-5182 Validation of Colloidal Activated Carbon for Preventing the Migration of PFAS in Groundwater
- ER18-1026 Rational Design and Implementation of Novel Polymer Adsorbents for Selective Uptake of Per- and Polyfluoroalkyl Substances from Groundwater
- ER20-5252 Anion Exchange Permeable Adsorptive Barriers (PABs) for In Situ PFAS Immobilization and Removal
- ER20-5100 In Situ PFAS Sequestration in AFFF-Impacted Groundwater
- ER21-1185 Thermal Decomposition of PFAS on GAC: Kinetics, Mass Balance, and Reuse of Reactivated Carbon
- ER21-1256 Develop Synergetic Novel Macrocycle-based Sorbents with Thermal Destruction for Enhanced PFAS Removal in Groundwater and Drinking Water Treatment

- ER21-1124 Assessment of Long-Term Effectiveness of Particular Amendments for In Situ Remediation of PFAS in Mixed Plumes
- ER22-3150 Engineering an “All-In-One” Biochar-Surfactant System for Enhanced PFAS Sorption and Reductive Degradation Using a Coupled Ultraviolet and Ultrasonication Approach
- ER22-3155 In Situ Sequestration of PFAS from Impacted Groundwater using Injectable High Affinity Cationic Hydrophobic Polymers
- ER22-3415 Novel Swellable Ionomers for Enhanced PFAS Sorption and Destruction
- ER22-7363 Rapid and Inexpensive Delivery of Particulate Carbon for In Situ PFAS Treatment in Groundwater
- ER22-3119 High-Capacity Sustainable Sorbents for Treatment of PFAS
- ER22-3194 Green Remediation of PFAS in Soil and Water

12.2.1.1 Granular Activated Carbon (GAC)

Treatment Description: GAC is an effective sorbent media for organics that has historically been used to reduce contaminants in a variety of environmental media. The information contained in this section describes ex situ GAC treatment in which water is extracted and transferred from the source of contamination and directed through the treatment system.

Treatment Mechanism: Removal of PFAS by GAC is a physical mass transfer process (refer to Section 12.2.1) from the aqueous phase onto solid media that does not involve or trigger any form of chemical degradation or transformation.

State of Development: The application of GAC as a treatment technology for PFAS removal has been practiced for over 15 years at more than 45 military installations, as well as several industrial sites and publicly owned treatment works (Forrester 2018) involving private and municipal drinking water supplies.

Effectiveness: The following references were used to support the treatability effectiveness discussion presented below for PFAS by GAC: Appleman et al. (2013); Burdick et al. (2016); Cummings (2015); Dickenson (2016); Ochoa-Herrera and Sierra-Alvarez (2008); Szabo (2017); Woodard, Berry, and Newman (2017); Zeng et al. (2020). These references also include more comprehensive bibliographies if further details are needed on specific topics or studies. Literature and supporting column studies have shown that newly placed GAC can reduce effluent concentrations for PFAS listed in USEPA Method 537.1 (Shoemaker and Tettenhorst 2018) to below analytical detection limits until initial breakthrough begins to occur. Because GAC is generally used to treat many common groundwater contaminants, it is capable of also treating most organic co-contaminants that may be present, with the primary impact being increased GAC consumption due to greater loading per unit of time, which may require more frequent change-outs.

Individual PFAS have different GAC loading capacities and corresponding breakthrough times (often defined as the number of bed volumes treated prior to detection in the effluent) (Eschauzier et al. 2012; Zeng et al. 2020). GAC removal capacity for PFOS is greater than PFOA, but both can be effectively removed (McCleaf et al. 2017). In general, shorter chain PFAS have lower GAC loading capacities and faster breakthrough times, but could be effectively treated if change-out frequency is increased. Figure 12-1 provides an example of removal curves and breakthrough information for several PFAS performed at a specific influent concentration based on vendor-supplied column studies.

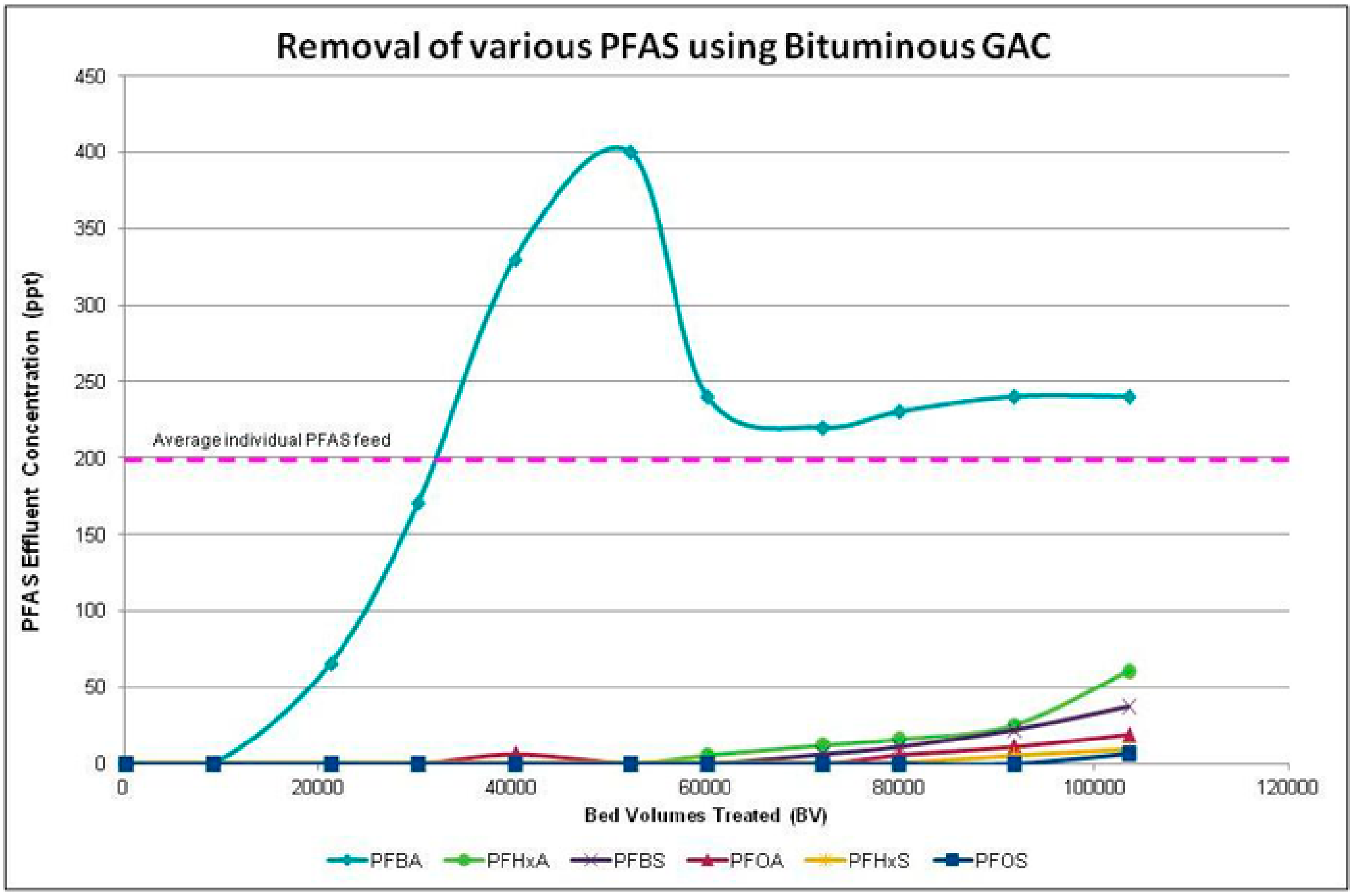


Figure 12-1. Example GAC removal curves at specific influent concentration (15-minute empty bed contact time).

Source: Used with permission from Calgon Carbon Corporation.

More studies are needed to confirm GAC treatment effectiveness for shorter chain PFAS or to identify complementary technologies/materials to supplement GAC removal capability. This may include studying the influence on sorption site competition from PFAS precursors that are often not quantified during the GAC system design. Recent accelerated column tests by vendors have shown the successful removal of a variety of PFAS, including the butyl (C4), pentyl (C5), and hexyl (C6) compounds (Appleman et al. 2013; Dickenson 2016; Brewer 2017; Zeng et al. 2020). Functional groups also impact the ability of GAC to adsorb PFAS. Compounds with sulfonate and sulfonamide groups are more readily adsorbed than those with carboxylates of the same chain length (Appleman et al. 2013; Dickenson 2016; Zeng et al. 2020). Studies in the developmental stage involve the use of other materials that can modify GAC surfaces to improve removal capabilities. Mixtures of powdered activated carbon, kaolinite, and amorphous hydroxide have been tested at the bench- and pilot-scale and have shown high removal rates for shorter chain PFAS in raw AFFF-impacted groundwater (Chiang 2017; Kempisty, Xing, and Racz 2018).

Most of the case studies on full-scale GAC-based systems used to treat PFAS in the literature are based on treatment of PFOA and PFOS in impacted drinking water sources. As such, limited information is available regarding the treatment of other PFAS, or PFAS in other source waters. The full-scale drinking water systems demonstrate that PFOA and PFOS can be removed to below analytical detection limits. More information is contained in the Table 12-1 Treatment Methods Table Excel File. Treatment of groundwater impacted with PFAS from an AFFF release area contaminated with PFAS such as fire training areas (FTAs) may require complex pretreatment and more frequent change-outs (higher influent concentrations compared to influent for drinking water treatment systems) and higher operation and maintenance (O&M) costs.

Design/Operating Considerations: Laboratory treatability tests (for example, rapid small-scale column testing (RSSCT) and accelerated column test (ACT)) are useful for evaluating treatability and determining initial design parameters. Larger scale pilot demonstrations are recommended to establish site-specific design parameters such as adsorption bed depth; GAC consumption rate to meet a given treatment objective; empty bed contact times (EBCTs); projections of breakthrough (based on bed volumes treated); and corresponding change-out frequency/costs. Column studies can also be used to compare loading capacity/breakthrough performance for different types of GAC (for example, different materials, preparation methods, and pore size distributions) offered by various vendors. These studies should always use site water to ensure that the effects of site-specific geochemical characteristics are assessed. Alternative analytical screening methods, for example, total oxidizable precursor (TOP) assay (Section 11.2.2.2), adsorbable organic fluorine (Section 11.2.2.4), and particle-induced gamma ray emission (PIGE) (Section 11.2.2.3), can be used to better estimate potential total mass load during the GAC remedial design phase. Field performance of GAC systems often varies significantly from that predicted in the RSSCT and other bench tests. Proper monitoring is critical to demonstrate that the desired performance is being achieved, especially at system start-up and following media change-out events.

Temporary and permanent GAC systems can be rapidly deployed and require minimal operator attention, if intensive pretreatment is not needed. The GAC media are placed in packed-bed flow-through vessels generally operated in series (lead-lag configuration). EBCTs of 10–20 minutes per vessel are typical (AWWA 2019). PFAS breakthrough is monitored by testing the water, at a minimum, between the lead and lag vessels. Additional sampling ports can be added (for example, at 25%, 50%, and 75% of the depth of the media). When breakthrough exceeds identified change-out criteria, the lead bed is taken offline and the spent GAC is removed and replaced with either new or reactivated GAC. The spent media are disposed off site by thermal destruction or can be thermally reactivated for reuse. Treatment can be continuous if the lag bed is used as the lead bed while the media in the latter are changed out. Figure 12-2 depicts a simple process flow diagram for a GAC treatment system.

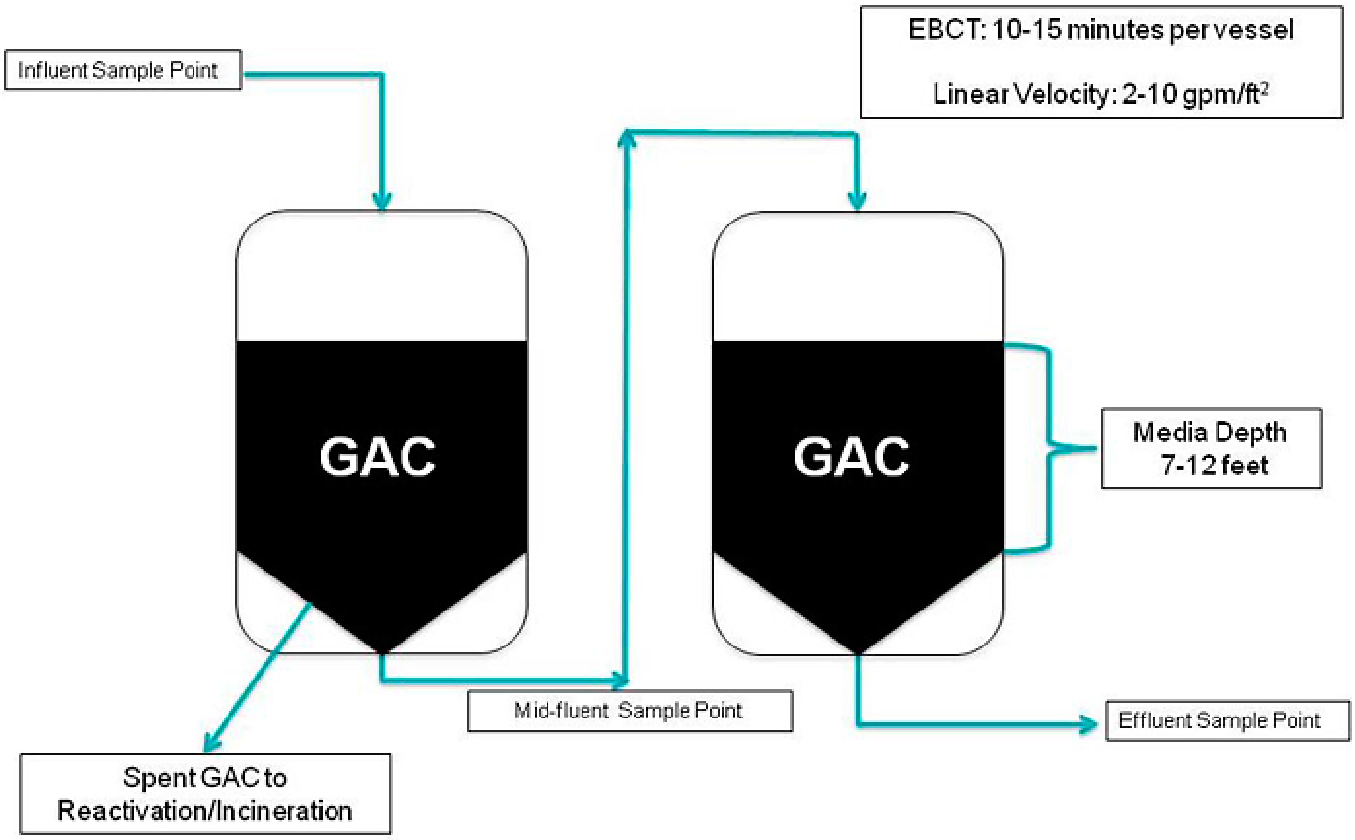


Figure 12-2. Typical GAC treatment system process flow diagram.
Source: Used with permission from Calgon Carbon Corporation.

Various GAC base materials (for example, bituminous coal, lignite coal, coconut shells) can be used for adsorption, though bituminous coal-based GAC has been used for the majority of existing sorption treatment systems for PFAS and current data show that bituminous-based products are more effective for PFAS removal (McNamara et al. 2018; Westreich et al. 2018). Specialized GAC formulations and coconut-based GAC can also be effective. Media selection and life cycle cost will depend upon a number of factors, including PFAS and co-contaminant concentrations, media availability, and pricing.

GAC treatment applications will evolve as analytical methods improve and regulatory concerns encompass an increasing number of PFAS. Shorter chain PFAS exhibit faster breakthrough times (Appleman et al. 2013), so particular attention needs to be given to these compounds if their removal is required. Alternative design optimization approaches or use of other technologies in combination with GAC (for example, ion exchange (IX) resins discussed in Section 12.2.1.2) can address high O&M costs that can be incurred for GAC treatment involving high influent PFAS concentrations, especially if shorter chain

PFAS must be removed. As discussed in Section 12.2.1.2, specialty single-use and regenerable IX resins have been developed that have higher loading capacities for shorter chain PFAS. GAC and IX can also be used in series to optimize removal capacity and minimize O&M costs, generally with GAC ahead of IX to remove non-PFAS organics and longer carbon chain PFAS, followed by IX to remove the shorter carbon chain PFAS. This approach has been implemented in the field and is presented in a case study in Section 15.2.2.1.

Spent GAC that contains PFAS can be thermally reactivated and reused, which may result in a lower cost media replacement option versus new GAC. However, some regulatory agencies may not allow the use of reactivated GAC for drinking water systems. NSF/ANSI standards require that the use of reactivated GAC for drinking water systems involve only media generated by the treatment system owner/operator and cannot include a mixture of GAC that originated from other sources. The management of spent media should be planned during the life cycle assessment phase and be documented as the treatment system is executed. Commercial facilities are available for thermal reactivation of spent GAC, which currently are not available for other sorption media and can offer a potential life cycle cost benefit for spent media disposal. Based on vendor feedback (Mimna 2017), commercial thermal GAC reactivation is performed at higher operating temperatures than steam or nitrogen regeneration systems, and may be capable of complete desorption and destruction of PFAS from spent GAC (Watanabe et al. 2016; Yamada et al. 2005). However, similar to incineration, additional studies are needed to investigate the fate of PFAS in the GAC reactivation process.

Sustainability: GAC ex situ PFAS water treatment systems have unique sustainability considerations as well as considerations in common with other ex situ PFAS sorption media water treatment systems (treatment complex construction, utilities, water collection and pumping, and discharge infrastructure). Major sustainability considerations unique to GAC systems are associated with:

- raw material collection and transportation
- GAC manufacturing and transportation
- larger media vessels relative to IX due to longer EBCTs
- larger treatment complex size due to larger vessels
- spent media transportation followed by reactivation, destruction, or disposal.

Multiple resources are available for performing sustainability assessments for sorption remedial designs (Amini et al. 2015; Choe et al. 2013; Choe et al. 2015; Dominguez-Ramos et al. 2014; Favara et al. 2016; Maul et al. 2014; Rahman et al. 2014; Ras and von Blottnitz 2012). Additional information is included in Section 12.9.

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER21-1185 Thermal Decomposition of Per- and Polyfluoroalkyl Substances on Granular Activated Carbon: Kinetics, Mass Balance, and Reuse of Reactivated Carbon
- ER21-1111 An Investigation of Factors Affecting In Situ PFAS Immobilization by Activated Carbon
- ER20-3034 Thermal Reactivation of Spent GAC from PFAS Remediation Sites
- ER19-5181 Improved Longevity and Selectivity of PFAS Groundwater Treatment Using Sub-Micron Powdered Activated Carbon and Ceramic Membrane Filter System
- ER22-7363 Rapid and Inexpensive Delivery of Particulate Carbon for In Situ PFAS Treatment in Groundwater

12.2.1.2 Ion Exchange Resin

Treatment Description: Ion exchange (IX) resin is an effective sorbent for other contaminants and has historically been used for a variety of water treatment applications (for example, nitrate, perchlorate, arsenic). To date, IX for PFAS removal from water is limited to ex situ applications.
IX resin options for removal of PFAS include single-use and regenerable resins. Single-use anion exchange resins are used until breakthrough occurs at a pre-established threshold and are then removed from the vessel and currently disposed of by high temperature incineration or by landfilling, where permitted. Regenerable resins are used until breakthrough but are then regenerated on site using a regenerant solution capable of returning a reduced capacity to the resin. Temporary and permanent IX systems can be rapidly deployed.

Treatment Mechanism: Removal of PFAS by IX is a physical mass transfer process from the aqueous phase onto solid media that does not involve any form of chemical degradation or transformation. IX resins with positively charged functional groups remove negatively charged PFAS from water by forming ionic bonds (the sulfonic and carboxylic acid heads of PFOS and PFOA are negatively charged at the typical range of pH values found in natural water). Simultaneously, the hydrophobic end of the PFAS structures can adsorb onto the hydrophobic surfaces of the IX resins, leading to increased ion exchange affinity on resins with hydrophobic backbones. Some PFAS at high liquid-phase concentrations (for example, 1 g/L) have been shown to also exhibit nonexchange sorption onto IX resins (Zaggia et al. 2016). However, the specific conditions and underlying mechanisms leading to this nonexchange sorption are not yet fully understood.

State of Development: Ion exchange technology has been used since the late 1930 for common water treatment processes like softening, demineralization, and selective contaminant removal. The development and use of selective resins for PFAS removal is relatively new but already well established. Single-use resins are now widely used for PFAS removal from water due to their simplicity of use and effectiveness in reducing regulated PFAS to nondetect (ND) levels. As of 2019, a limited number of regenerable IX systems have been installed in full-scale applications after successful pilot testing. Collection of data on longer term treatment and on-site regeneration of the IX resin is ongoing at a case study site (Section 15.2.2.2). In general, the removal capacity of the single-use resin is higher than that of regenerable resin, and single-use resin can be more fully exhausted in a lead-lag vessel configuration than regenerable resin. The relative removal efficiency of regenerable and single-use resins depends upon PFAS and co-contaminant influent concentrations and treatment goals.

Effectiveness: Selective IX has been demonstrated to reduce concentrations for a broad suite of PFAS at the bench and field scale for influent concentrations as high as 100s of parts per billion (ppb) total PFAS to below analytical detection limits in effluent (Kothawala et al. 2017; McCleaf et al. 2017; Woodard, Berry, and Newman 2017; Zeng et al. 2020). The affinity of such resin for common subgroups of PFAS generally follows the order PFSA > PFCA. Within each subgroup, affinity increases with increasing carbon chain length, and are not necessarily sequential (that is, longer chain PFCA may be adsorbed better than shorter chain PFSA).

In general, IX resin systems being used for PFAS removal are not installed with the intention of removing co-contaminants. Co-contaminants (including organic and inorganic compounds) may significantly reduce the removal capacity of IX for PFAS, although this depends on the selectivity of the IX resin. Because of the variability in resin behavior, as well as site-specific chemistry and co-contaminants, influent characterization is needed to assess potential pretreatment options to remove co-contaminants. Pretreatment is necessary to prevent fouling (for instance, by iron or manganese) and preserve resin capacity for PFAS removal, particularly in the context of remediation where complex co-contaminant chemistry is expected. Pretreatment needs for drinking water applications may be simpler or not required. Another consideration for drinking water utilities is that, depending on the type of IX resin used, a freshly installed IX column may cause short-term disruptions in pH or corrosivity of effluent water, which may necessitate mitigation strategies such as effluent blending or diverting initial effluent to waste (Smith et al. 2023).

Single-use PFAS-selective IX resins are well-suited to treat low-concentration PFAS such as is typically encountered in potable water treatment systems, where media change-out would be infrequent. Figure 12-3 provides an example of removal curves and breakthrough information for a number of PFAS at the specified influent concentrations (in the legend) based on vendor-supplied data for a full-scale single-use system. Breakthrough is calculated as the ratio of the effluent concentration to the influent concentration (C/C_0). It is not uncommon to observe fluctuations in the breakthrough curve in some field pilot studies due to varied influent concentrations over time. For example, after a resin unit is in equilibrium with one PFAS at an initially higher influent concentration, a lower concentration influent can desorb PFAS from the resin, resulting in breakthrough higher than 100%. The typical breakthrough order observed in Figure 12-3 is expected to be similar for various anion exchange resins, as relative ionic bond strengths and carbon chain lengths result in shorter chain PFCAs to longer chain PFCAs desorbing first, followed by shorter chain PFSAs to longer chain PFSAs. Similar responses also apply to GAC.

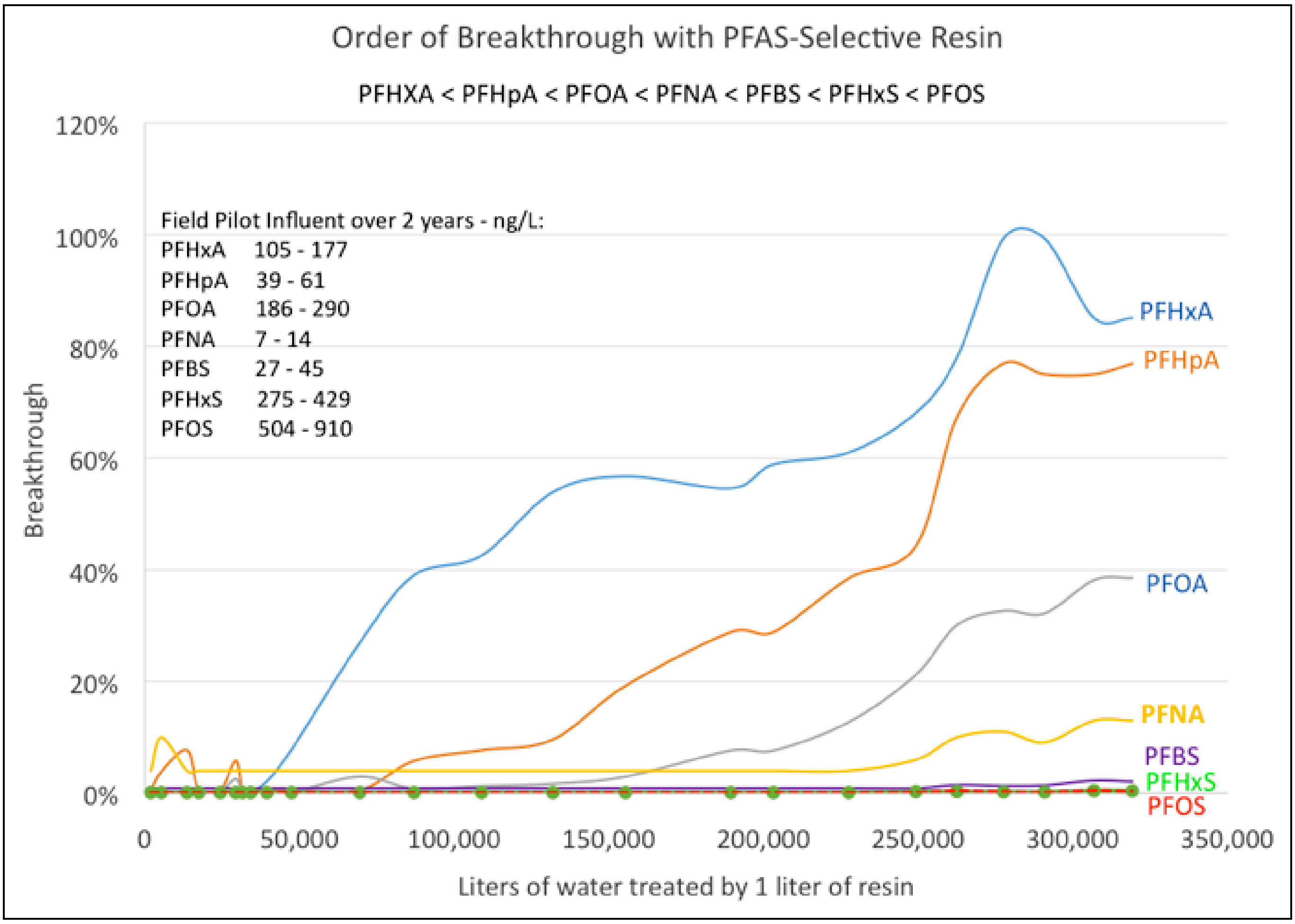


Figure 12-3. Example of IX removal curves from a field pilot study at specific influent concentrations (2.5-minute EBCT). (Note: Initial concentrations in ng/L or ppt.)

Source: Used with permission from Purolite Corporation.

Regenerable IX is not yet approved per NSF 61 for potable water treatment. Regenerable resins are better suited for removal of higher concentration PFAS where the savings realized from reusing the treatment media outweighs the cost of frequent replacement of nonregenerable media. Regenerable IX becomes more efficient than single-pass media when flow rate and concentration increase and RAOs go down, because these factors increase the frequency and volume of media change-outs for single-pass media. These factors also increase the regeneration demand; however, regeneration frequency can be extended by using larger vessels. Cost efficiency and viability of regenerable IX relative to single-use IX and GAC media are evaluated in ESTCP ER18-5015.

An example of typical breakthrough curves for regenerable resin system is shown in Figure 12-4. On the graph the y-axis is sample concentration/original concentration (C/C_o), also note the influent PFAS concentrations (in the legend) in Figure 12-4 are higher (reported in ppb) than presented in Figure 12-3 (reported in ppt). Additional details on a regenerable resin system are provided in a case study in Section 15.2.2.2. The cost effectiveness for regenerable resin systems could increase significantly (and thus impact the system's practical implementability) when a central regeneration facility can be shared amongst multiple PFAS removal systems. The application of single-use versus regenerable resins must be evaluated on a site-specific basis.

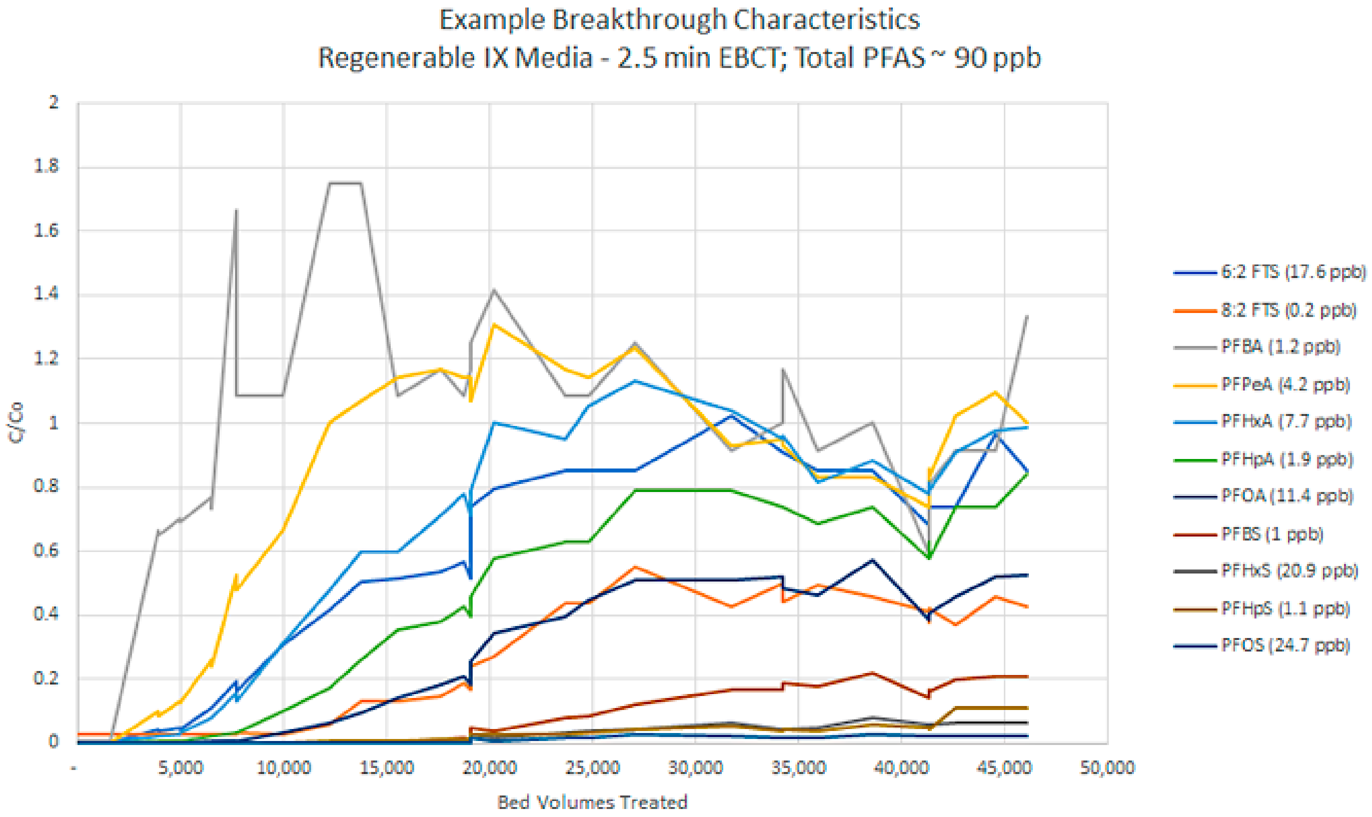


Figure 12-4. Example of regenerable IX removal curves from a field pilot study at specific influent concentrations (2.5-minute EBCT). (Note: Initial concentrations in µg/L or ppb.)

Source: Used with permission from ECT2.

Design/Operating Considerations: IX treatment systems are configured similarly to GAC systems. Refer to Section 12.2.1 for a description of GAC systems that also applies to IX systems, and Section 12.2.1.2 for fouling considerations. Figure 12-5 depicts a simple process flow diagram for a single-use IX treatment system.

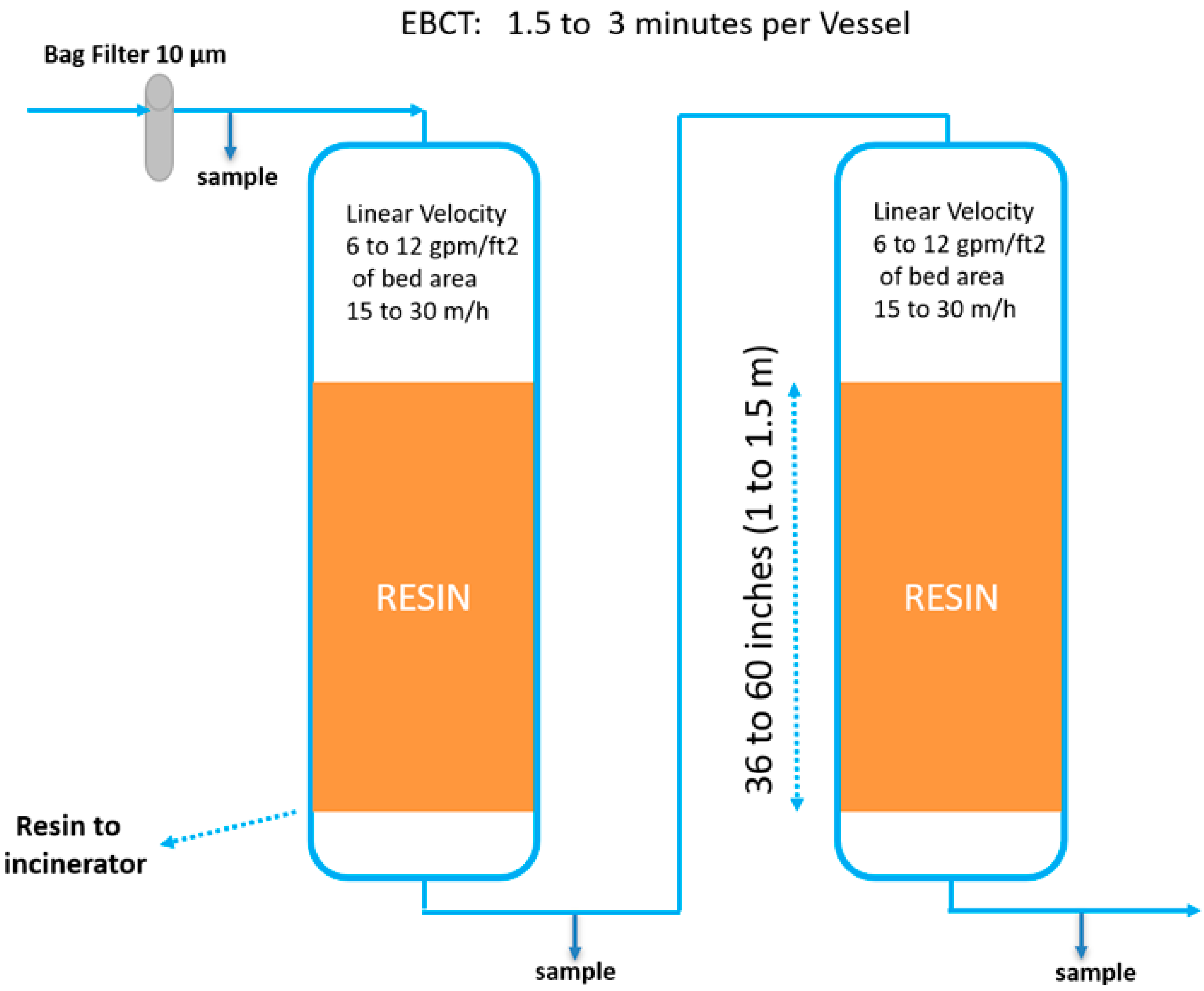


Figure 12-5. Single-use IX process flow diagram.

Source: Used with permission from Purolite Corporation.

Selective IX requires a relatively short EBCT of 1.5–5 minutes per vessel of resin (Boodoo 2017), hence smaller resin volumes and smaller, less costly treatment vessels versus GAC, which requires EBCTs of about 10–20 minutes per vessel (AWWA 2019; Brewer 2017) and correspondingly larger volumes of media. Selective IX resins have shown high operating capacities when removing trace levels of PFAS (for example, 100,000–400,000 bed volumes; refer to Figure 12-5), resulting in fewer change-outs of spent IX resin and reduced O&M costs. Capacity depends on the concentrations of competing anions, such as sulfate and nitrate, and on the specific PFAS breakpoint chosen for resin change-out. While lead-lag vessel design is standard, if space allows, it is possible to use a lead-lag-polisher design with three resin vessels in series. The addition of a polisher vessel provides a factor of safety for increasing the loading to the lead vessel, thereby reducing change-out frequency and cost. A lead-lag-polisher design will usually result in reduced operating expenses (OPEX) but higher capital expenses (CAPEX). Therefore, the decision to use it must be done on a case-by-case basis. Pretreatment may mitigate fouling and improve performance.

For drinking water supplies with relatively clean water, the industry is rapidly moving to rely more and more on vendor-provided modeling for common PFAS with such modeling including predicted breakthrough curves and resin capacities for specific PFAS breakpoints. Modeling can easily evaluate a variety of “what-if” scenarios, such as changing water chemistries and assessing the economics of operating to nondetectable levels or stricter regulatory limits for selected PFAS. Because of the USEPA (2022) health advisories and the USEPA proposed National Primary Drinking Water Regulations (NPDWRs) for MCL and MCLG values that are currently under public review (USEPA 2023), and the current inability of most labs to analyze to these low levels, modeling of treatment may be needed to evaluate how much faster theoretical breakthrough will occur and what extra cost will be incurred.

Pretreatment for several influent water parameters has been recommended (Section 12.2.1). Natural organic matter (NOM) is of particular importance because it occurs at concentrations that are three orders of magnitude higher than PFAS. Therefore, NOM can compete for the same ion exchange sites on the resin and can also blanket the surface of the resin beads, thereby blocking access for PFAS to the internal sites on the beads. The negative impact of NOM in groundwater on resin capacity can usually be factored in at the design stage if appropriate data and models are available, because NOM is usually present at less than 2 mg/L. However, when treating surface water with NOM concentrations that can seasonally rise to 5–10 mg/L (and even higher), it is particularly important to consider negative impact on resin capacity. Dixit et al. (2020) evaluated the impact of various dosages of Suwanee River NOM on resin capacity for PFAS and showed decreases of 22%, 50%, and 68% in resin capacity when adding dosages of 5, 10, and 20 mg/L NOM and using an organic scavenger acrylic resin in isotherm test solutions.

Despite the growing adoption of modeling, pilot testing is still recommended when evaluating breakthroughs for multiple PFAS or when the impact of TOC or other contaminants such as iron and manganese must be known to determine pretreatment requirements. In such cases, a technique referred to as accelerated piloting may be used, in which monitoring ports in the pilot column are set at 25%, 50%, and 100% of the resin height. This allows results to be obtained more quickly, but it is with the understanding that the breakthrough profile for each of the ports will be somewhat different. There is also growing interest in using the rapid small-scale column testing (RSSCT) technique for resins. Originally developed for use with GAC, the RSSCT technique uses crushed GAC and shorter EBCTs to quickly predict operating capacity. At this time, it is too early to know if this technique will reliably work for spherical resin beads when crushed.

Selective IX resins show much higher selectivity for PFAS than for common anions in water such as sulfate (SO_4^{2-}), nitrate (NO_3^-), chloride (Cl^-), and bicarbonate (HCO_3^-). However, these common anions are generally present in water at about three orders of magnitude higher than PFAS and will be the main competitors for the ion exchange sites on the resin. As such, they will largely determine the operating capacity of such resins. The choice between single-use and regenerable resins will in part be determined by the expected service period before the resin must be either replaced (single-use) or total regeneration costs (including capital and transportation costs). As PFAS concentration increases or as effluent criteria decreases, the frequency of regeneration or media change-out increases. As regeneration or media change-out increases, regenerable IX becomes more long-term cost-effective, if indeed the cost of regeneration is less than the cost of media replacement.

Regenerable IX resin can be reused long term if protected from contact with strong oxidizing agents, foulants, and chemical/mechanical stresses. In recent years, both pilot-scale and full-scale regenerable IX systems have demonstrated long-term durability of the media. One study, ESTCP ER18-5015, demonstrated greater than 95% removal capacity for regenerated media as compared to new media over six loading and regeneration cycles. IX regeneration is a chemical process. Field-demonstrated regeneration uses a solvent-brine solution in which the brine dislodges the ionic head of the PFAS molecule and the solvent desorbs the fluorinated carbon chain (or “tail”) from the IX resin (Woodard, Berry, and Newman 2017; Amec Foster Wheeler 2017). For a regenerable IX system, it is possible to concentrate the regenerant solution and reuse it by distillation (Nickelsen and Woodard 2017). The distillate residue then contains a concentrated PFAS waste that can be super-loaded onto specialized resin to create a small volume of solid waste that can be managed by off-site disposal or potentially through on-site destruction using other technologies currently under development and discussed in Table 12-1 Treatment Methods Table Excel File (for example, plasma or electrochemical destruction).

By combining various technologies in a treatment train approach, it may be possible to achieve better overall treatment at lower cost (Section 12.8).

Sustainability: Ex situ ion exchange water treatment systems have unique sustainability considerations in addition to those shared with other ex situ sorption media water treatment systems. Major sustainability considerations for ion exchange systems are associated with:

- raw materials, which are generally synthetic, petroleum derivatives
- resin manufacturing and transportation, including from overseas
- regeneration materials, energy, and labor for regenerable IX media
- disposal or destruction of regeneration residuals
- long-distance transportation of spent media to limited available disposal outlets
- energy-intensive destruction methods for spent media

Related Past, Ongoing, and Recent Research Funded by SERDP (ER) and Water Research Foundation (WRF):

- ER18-1027 Ex Situ Treatment of PFAS-Contaminated Groundwater Using Ion Exchange with Regeneration
- ER18-1063 Regenerable Resin Sorbent Technologies with Regenerant Solution Recycling for Sustainable Treatment of PFASs
- ER 18-5015 Removal and Destruction of PFAS and Co-Contaminants from Groundwater via Groundwater Extraction and Treatment with Ion-Exchange Media, and On-site Regeneration, Distillation, and Plasma Destruction
- ER 18-1306 Combined In Situ/Ex Situ Treatment Train for Remediation of Per- and Polyfluoroalkyl Substance (PFAS)-Contaminated Groundwater
- ER18-5053 Evaluation and Life Cycle Comparison of Ex Situ Treatment Technologies for Poly- and Perfluoroalkyl Substances in Groundwater
- WRF 4913 Investigation of Treatment Alternatives for Short-Chain PFAS
- ER20-5252 Anion Exchange Permeable Adsorptive Barriers (PABs) for In Situ PFAS Immobilization and Removal
- ER18-1320 Electrochemical Oxidation of Perfluoroalkyl Acids in Still Bottoms from Regeneration of Ion Exchange Resins

12.2.2 High-Pressure Membranes

In the context of this document, high-pressure membranes are defined as those meeting the characteristic separation performance of nanofiltration (NF) and reverse osmosis (RO) membranes. Both the NF and RO membrane categories span a range of selectivity (for example, loose NF to tight RO) and may rely on different rejection mechanisms to support the separation of PFAS from impacted water. However, under the correct application, both technologies have been proven to effectively remove PFAS from a variety of feed water sources. This technology is generally considered more applicable to high volume, low concentration liquids than low volume, high concentration liquids.

12.2.2.1 Nanofiltration (NF)

NF is a form of membrane technology that is pressure-driven and shown to be effective in the removal of PFAS (Tang et al. 2007). This method of filtration provides high water flux at low operating pressure (Izadpanah and Javidnia 2012). Typically, NF membranes exhibit high rejection of polyvalent ions and other molecules of sufficient size, but are susceptible to permeation by monovalent ions (for example, sodium, chloride) and smaller molecules. The most common membrane module configurations are spiral-wound (consisting of flat sheet membrane material wrapped around a central collection tube); however, hollow fiber NF modules may also be available for applications with higher fouling potential.

Available data on the removal of PFAS via NF consist of laboratory-scale tests performed on flat sheet membrane coupons (laboratory-scale sections of the membranes to be tested) and one full-scale drinking water treatment plant using an NF treatment train. Therefore, variations in performance due to fouling, flux, and concentration distributions in standard spiral-wound membrane configurations have not been characterized (Boo et al. 2018).

NF membranes tested include the DuPont (formerly Dow FilmTec) membranes NF-270, NF-200, and NF-90, and the SUEZ (formerly GE Water & Process Technologies) DK membrane. Reported rejections were generally > 95% for PFAS with molecular weights ranging from 214 grams per mole (g/mol) to 713 g/mol, though some compounds had lower rejections (PFPeA at 70% and perfluorooctane sulfonamide at 90%) (Steinle-Darling and Reinhard 2008; Appleman et al. 2013). Effective full-scale removal of PFAS by NF membranes was confirmed based on nondetectable PFAS concentrations (<4 ng/L) in NF permeate (Boiteux 2017). Salt passage for PFOS was reported to range from < 1% for the tighter NF-90 membrane to about 6% for the looser NF-270 and DK membranes (Tang et al. 2007). New research has focused on functionalizing membrane surfaces to improve PFAS selectivity (for example, Johnson et al. 2019). An appropriate disposal or treatment of the membrane concentrate stream needs to be considered, especially the application of high-pressure membranes for inland communities. Fluoropolymers may be used to manufacture membranes, which brings into consideration the need for PFAS-bearing reagents to manufacture the membranes, disposal of manufacturing byproducts, and disposal of spent filters.

12.2.2.2 Reverse Osmosis (RO)

RO is a technology used to remove a large majority of contaminants (including PFAS) from water by forcing water, under pressure, across a semipermeable membrane as described below. A typical RO system consists of three streams: the untreated water (feed), the treated water (permeate), and the residual reject water (concentrate). The most common membrane module configuration is spiral-wound, which consists of flat sheet membrane material wrapped around a central permeate collection tube. Like most treatment technologies, RO is seldom used alone, but rather as part of a treatment train. Most efficient RO performance may require pretreatment. RO-treated effluent (that is, permeate) may require supplemental management to mitigate the corrosivity of demineralized water.

Treatment Description: RO membranes are effective in removing most organic and inorganic compounds from water solutions. In recent years, new polymer chemistry and manufacturing processes have improved efficiency, lowering operating pressures and reducing operating costs (Lau et al. 2012). As a result, RO membranes are increasingly used by industry to concentrate or remove chemicals. RO is commonly used around the world in household drinking water purification systems, the production of bottled mineral water, self-contained water purification units (for example, for branches of the U.S. military), and industrial applications (for example, water supply to cooling towers, boilers, and deionized water). The largest application of RO is in desalination. In comparison, high-pressure membrane applications typically have higher capital and operating costs relative to GAC or IX systems designed for PFAS removal.

Treatment Mechanism: RO removes compounds from water solutions by forcing pressurized water across a semipermeable membrane. The driving pressure required in RO systems is a function of multiple factors, including the osmotic pressure of the feed water, the membrane type, and the system configuration. Typically, size exclusion is the prevailing mechanism for contaminant removal in RO membrane systems. The physical barrier (that is, semipermeable membrane) underlying the size exclusion removal mechanism provides additional assurance regarding the treatment of PFAS spanning a wide range of physical and chemical properties. Treated water (permeate) passes through the membrane and the rejected water (concentrate) is collected for disposal or discharge, depending on the nature of the compounds present.

State of Development: RO has been studied in bench-scale studies and pilot plants for wastewater and drinking water applications, offering the opportunity to compare both treatments operating simultaneously (Tang et al. 2006; Tang et al. 2007; Flores 2013; Glover, Quiñones, and Dickenson 2018; Dickenson 2016; Merino et al. 2016; Appleman 2014; Snyder 2007). This allows for an understanding of the effectiveness of traditional drinking and wastewater treatment methods alongside PFAS-specific technologies.

Effectiveness: Pretreatment is important when working with RO membranes. Membranes can be susceptible to fouling (loss of production capacity) because some accumulated material cannot be removed from the membrane surface during routine cleaning and maintenance procedures. Therefore, effective pretreatment to mitigate the formation of organic or inorganic foulants is a necessity for many RO systems. Pretreatment technologies would be specific to the RO feedwater quality.

RO removal of PFAS from various waters (for example, semiconductor wastewater, drinking water, surface water, and reclaimed water) has been studied and several studies have combined RO with nanofiltration (NF). PFOS removal > 99% was achieved using four different types of membranes over a wide range of feed concentrations (0.5–1,500 ppm [mg/L]) (Tang et al. 2006). Another study by Tang et al. (2007) tested five RO and three NF membranes at feed concentrations of 10 ppm PFOS over 4 days. The PFOS rejection and permeate flux performances were > 99% for RO and 90–99% for NF. The use of RO and NF as advanced drinking water treatments is still limited, but both technologies have been shown to be successful for the removal of longer chain (> C5) PFAAs (Loi-Brügger et al. 2008; Tang et al. 2006).

Thompson et al. (2011) studied the fate of perfluorinated sulfonic acids (PFSAs) and carboxylic acids (PFCAs) in two water reclamation plants that further treat water from wastewater treatment plants (WWTPs) in Australia. One plant (Plant A) used adsorption and filtration methods alongside ozonation; the other (Plant B) used membrane processes and an advanced oxidation process to produce purified recycled water. At both facilities, PFOS, perfluorohexane sulfonate (PFHxS), perfluorohexanoate (PFHxA), and PFOA were the most frequently detected PFAS. Comparing the two reclamation facilities, Plant A showed some removal during the adsorption/filtration stages. Overall, however, Plant A failed to completely remove PFOS and the PFCAs shorter than PFNA in chain length. All PFAS present were removed by RO at Plant B from the finished water to concentrations below detection and reporting limits (0.4–1.5 ng/L).

Design/Operating Considerations: This section refers to design and operating considerations for both RO and NF systems. Typical high-pressure membrane systems can achieve recoveries between 70% and 85%, with some high recovery applications able to achieve >95% recovery (Bond and Veerapaneni 2008; Stover 2013). Recovery is defined as the ratio of treated effluent (permeate) to feed water. The feed water not accounted for in the permeate is the reject or concentrate. In conventional systems, the concentrate fraction may represent 15%–30% of the feed flow or <5% of the feed flow for high recovery applications. In conventional or high recovery high-pressure membrane systems, recovery is typically limited by the feed water quality.

In the process of planning and implementing a high-pressure membrane filtration system, there are several important issues that affect system design and operation and could impact system performance and thus PFAS removal. These issues include membrane flux, water quality, and temperature.

- **Membrane Flux:** One of the major challenges in the application of membrane technology is fouling (significant flux loss due to continuous accumulation of colloidal and organic matter, precipitation of inorganic salts, and/or microbial growth). There are several ways to mitigate fouling: (1) changing operating conditions, (2) modifying the membrane, and (3) modifying the feed by adding antifoulants prior to filtration system (pretreatment) (Roux et al. 2005). Adequate pretreatment and appropriate membrane selection can slow the fouling rate, but routine membrane cleaning is an essential step in maintaining the performance of the membrane process. Membrane replacement is a necessary part of plant operation to maintain the quality of the produced water (Abdul-Kareem Al-Sofi 2001). Although there are a number of cleaning techniques, such as physical or chemical or a combination of both, chemical cleaning methods are more widely used by NF and RO industries for membrane cleaning and regeneration. Spent cleaning solution may contain PFAS and would need to be managed properly.
- **Water Quality:** Because water quality can have a significant impact on membrane flux, feedwater quality is also a primary design consideration for membrane filtration systems. Poorer water quality (high suspended and dissolved solids, co-contaminants) will reduce flux, which in turn increase the necessary membrane area and required number of membrane modules, adding to both the cost and the size of the system. However, pretreatment can often improve feedwater quality at a lower cost than additional membrane area. Because RO is a relatively expensive technology, efforts to improve water quality with pretreatment processes ahead of the RO membranes (filtration, precipitation; see Section 12.7) will result in reduced capital and operating costs.
- **Temperature:** Like other water quality parameters such as turbidity and total dissolved solids (TDS) (for NF/RO systems), the temperature of the feedwater also affects the flux of a membrane filtration system. Water becomes increasingly viscous at lower temperatures; thus, lower temperatures reduce the flux across the membrane at constant transmembrane pressure or alternatively require an increase in pressure to maintain constant flux. Because rejection decreases as membrane pores expand at higher temperatures, more permeation of PFAS across the membrane could occur at higher operating temperatures.

Sustainability: The environmental footprint for this technology includes energy source and consumption during treatment system operation, as well as manufacturing/disposal of pretreatment/treatment media (examples may include solids from upstream precipitation/coagulation or microfiltration, used cartridge filters, and worn RO membrane modules) and cleaning solutions to maintain the membrane. RO requires power for high-pressure pumps and the management of concentrate, which can be energy intensive.

An issue inherent to contaminant removal by membrane processes is the disposal of the PFAS-enriched concentrate, which must be carefully considered. Development of effective treatment methods for the concentrate entails evaluating significant parameters, such as volume generated, concentration, characteristics of the feedwater, and operational conditions, and using well-verified analytical methods to detect trace amounts of contaminants. Concentrate treatment and management alternatives remain an active area of research (Joo and Tansel 2015). Tow et al. (2021) documented treatment and management alternatives specifically focused on PFAS-impacted concentrates. Tow et al. (2021) reviewed 22 different PFAS-impacted concentrate treatment or management alternatives that included application of additional separation technologies (for example, adsorbents, foam fractionation), destructive technologies, and disposal/sequestration options. There are numerous options to consider for PFAS-impacted concentrate treatment and/or management, and identifying the best alternative will be a function of site-specific factors including location, volume of concentrate, PFAS concentrations, and presence of co-contaminants.

12.2.3 Foam Fractionation

Treatment Description: Foam fractionation is a subset of a larger treatment of practice known as adsorptive bubble separation technologies. Foam fractionation is a physical separation process that traditionally uses air and turbulence to generate bubbles rising through a water column to strip amphiphilic substances such as PFAS from the bulk liquid (Lemlich and Lavi 1961; Lemlich 1972). Foam fractionation technology has been used for decades in the commercial-scale aquarium business to clean water by separating and removing proteinaceous waste and has been advanced to multistage configurations for PFAS separation and concentration. Amphiphilic PFAS adsorb to the surface of the bubbles as they rise upwards. PFAS that accumulate at the top of the column as a concentrated foamate are then removed for further treatment or disposal. This process has been implemented for ex situ water treatment, and in situ, down-hole foam fractionation approaches have also been tested but are in less developed stages.

Treatment Mechanism: Air or other gaseous bubbles are introduced into a PFAS-containing liquid, which causes amphiphilic PFAS and other amphiphilic organic compounds to adsorb to the bubble surface, separating them from the bulk water. As the bubbles migrate upwards, PFAS are removed from the bulk liquid. The top foamate layer is concentrated in PFAS and can be removed passively via overflow or actively via vacuum suction for further treatment. The extent to and rate at which PFAS are removed depends on individual PFAS physical chemical properties, background water quality properties, and operational considerations discussed in the subsequent sections. Buckley et al. (2021) presented a detailed review, including description of key separation mechanisms, of foam fractionation for water treatment. Stevenson and Li (2014) produced a monograph on the theory and practical implementation of foam fractionation.

State of Development: Foam fractionation has been studied at the bench scale and implemented at the pilot- and full-scale level to remove PFAS in groundwater (Burns et al. 2021) leachate (Burns et al. 2022; Newman 2022; Smith et al. 2022; McCleaf et al. 2021; Robey et al. 2020), and industrial water (Smith et al. 2023). The base technology was developed and built in Australia and is currently operating at full-scale in Queensland, Australia (see the case study in Section 15.2.4.1 and Burns et al. (2021). Foam fractionation systems have successfully removed PFOS and PFOA to low level parts per trillion levels (Burns et al. 2021; Burns et al. 2022; Newman 2022; Smith et al. 2022; Smith et al. 2023). Additional research is underway to promote removal of short-chain PFAS such as PFBA and PFBS in foam fractionation, which to date have not been effectively removed across all waters tested. Short-chain carboxylates have proven especially difficult to remove. Foam fractionation is provided by multiple commercial vendors in the United States, Europe, Canada, and Australia. Maximum flow rates implemented in the field are on the order of 50–150 gallons per minute in single fractionators. Scale up to larger foam fractionators is theoretically feasible, and multiple fractionators in parallel have been deployed to treat higher flow rates.

Effectiveness: Foam fractionation is highly effective at removing PFOS and PFOA and longer chain PFAS (Burns et al. 2021; Newman 2022; Burns et al. 2022; Smith et al. 2022) to single-digit parts per trillion levels, but its performance at removing PFAS with fewer than six perfluorinated carbons remains mixed. Removal of PFAS during foam fractionation is dependent upon individual PFAS adsorption coefficients (Burns et al. 2022), which are derived from the adsorption isotherm under specific conditions for each compound for uptake onto a gas/liquid interface. As with adsorptive media, perfluoroalkyl sulfonates of an equivalent perfluoroalkyl chain length are removed during foam fractionation more effectively than perfluoroalkyl carboxylates (for example, PFHxS is removed more effectively than PFHpA). Researchers and practitioners have identified that chemical additions, often in the form of cationic surfactants, can improve the removal of PFBS, PFHxA, PFPeA, and PFBA (Buckley et al. 2022; Newman 2022; Buckley et al. 2023; Vo et al. 2023). A cationic surfactant that successfully removed PFBA in a deionized solution of sodium chloride was unable to remove PFBA from landfill leachate under similar operating conditions (Buckley et al. 2023; Vo et al. 2023). Foam fractionation is also effective at removing a wide range of PFAS concentrations (for example, nanograms per liter to milligrams per liter); however, greater orders of magnitude removal require longer hydraulic retention times and/or additional stages of treatment.

Foam fractionation can also be effective for PFAS removal on a wide range of water quality types without the need for additional pretreatment. The complexity of the leachate matrix is likely one reason why foam fractionation has been trialed so extensively on leachate (Burns et al. 2022; Newman 2022; Smith et al. 2022; McCleaf et al. 2021; Robey et al. 2020). Compared to PFAS treatment with GAC, anion exchange resin, and reverse osmosis, foam fractionation performance is impacted in a much more limited way by background analytes such as TOC, dissolved metals, and hardness that foul adsorptive media and membranes. The primary constituents that concentrate into the foamate through a foam fractionation process are suspended solids, PFAS, and other surfactants, including any used to enhance the foaming process, while other water quality characteristics such as dissolved anions and cations remain similar in concentration to the source water. See the case study in Section 15.2.4.2.

Site-specific water chemistry does impact foam fractionation performance, so laboratory testing is recommended to optimize pilot design. Some researchers have reported a higher degree of removal during foam fractionation as TDS increases in the source water (Buckley et al. 2022).

Design/Operating Considerations: Design parameters that can affect the performance of ex situ foam fractionators include the following:

- The non-PFAS characteristics of the water, including constituents that can increase or diminish the natural foaming potential of the water
- The hydraulic retention time of the fractionator; hydraulic retention times reported in the literature for stripping fractionators have typically fallen within the range of 10–60 minutes (Smith et al. 2022; Buckley et al. 2022; Newman 2022)
- Countercurrent or co-current flow of gas and water

- The amount, speed, and bubble size of gas introduced per volume of water in the fractionator. The bubble size is partially related to the type of gas introduced, with ozone bubbles typically introduced with a smaller size than air.
- The amount of turbulence introduced along with the gas. More turbulence tends to increase foam generation and has an overall beneficial impact on PFAS removal
- The height of the water column relative to the foam collection point (that is, a weir or overflow)
- The mechanism of foamate removal, which can include traditional spillover or application of a vacuum process
- The number of treatment units operated in series
- Batch, semicontinuous batch, or continuous flow operation, which is discussed in more detail below
- The introduction of chemical agents to increase foaming or removal of particular PFAS

In ex situ foam fractionation processes, foam fractionation can be operated in either “stripping-wet” or “enriching-dry” modes (Smith et al. 2023). In stripping-wet mode, the top of the water column is located very close to the weir or overflow so that foamate may readily exit the fractionator. This mode of operation does not allow for significant foam drainage of interstitial liquid prior to foamate exiting the fractionator, so a relatively wet foam is generated. Under the enriching-dry mode, the fractionator fill volume is set at a larger distance from the weir or overflow to allow for a greater degree of drainage of excess interstitial liquid from the foamate. The enriching-dry mode produces a low volume of foamate, but typically results in target PFAS remaining in the treated water exceeding low-level PFAS treatment criteria, so the underflow or raffinate will require further treatment. Setting the fill volume too low in relation to the weir can result in poor treatment due to ineffective collection of foamate.

Practitioners may elect to adopt either a single-batch, multistage semicontinuous batch, or continuous flow-through design depending upon PFAS target treatment criteria, required throughput, and desire to further reduce the foamate volume prior to proceeding to additional treatment. Foam fractionation setup as a batch process typically configures the stripping-wet stage first, followed by one or multiple enriching-dry stages. Foam setup as a continuous flow-through process can configure the first stage to operate in either stripping-wet or enriching-dry mode, followed by one or more additional stages to be able to reach the treatment goals by the final stage, where water height in each successive stage will require careful management. Each of the configurations has relative benefits and drawbacks. For example, batch typically has lower flow-through capacity compared to flow-through designs, but has faster stripping times per fractionation column.

The stripping of PFAS from bulk phase liquid into a gaseous phase raises relevant concerns about worker exposure to PFAS and other compounds that may be stripped out of the aqueous phase via the operation of these systems. In the Smith et al. (2023) study, PFAS were measured in aerosols and air around a foam fractionator; the mean measured sum of PFAS was twenty-seven times higher than the concentration measured at a reference site, with the highest concentration measured closest to the outlet of the fractionator. The composition of PFAS measured was also similar to that measured in the foamate. Emissions control devices and enclosure of all foam fractionator components may be needed to mitigate gaseous PFAS releases from the foam fractionation process.

The ultimate disposition of the resulting PFAS-enriched foamate varies. Options include concentrating the foamate onto an adsorptive media or delivering it to an aqueous destruction process. The concentrated nature of PFAS in foamate makes it a good candidate for pairing with various PFAS destruction technologies, and it also promotes increased loading onto media. Electrochemical oxidation of foamate has been reported in the peer-reviewed literature with only partial ability to break down target PFAS (Smith et al. 2023). The TDS concentration in the final waste foamate created by foam fractionation is appreciably lower than that of residual waste material from the regenerable ion exchange resin treatment process, and may therefore have an advantage when paired with certain PFAS destruction processes.

Sustainability: The environmental footprint for this technology includes energy source and consumption during treatment system operation. One provider has reported a system energy consumption of 0.8 kWh/m3 in a semibatch system with a 250 m3 throughput that performs secondary and tertiary foam refractionation (Burns et al. 2021). As longer hydraulic retention times and more stages of refractionation/enrichment of foamate are introduced, energy consumption per volume of water treated increases. The PFAS-enriched foamate requires disposal, often via loading onto an adsorptive media. Destruction of PFAS in foamate is also under consideration, and research activities supporting PFAS destruction in foamate are identified in the ongoing research funded by SERDP/ESTCP. Unlike RO, the concentrate generated by foam fractionation offers an appreciable reduction in volume and is thus better suited for a low throughput, high energy consumption PFAS destruction technology.

Related Past, Ongoing, and Recent Research Funded by SERDP or ESTCP:

- ER19-5075 In Situ Treatment of PFAS Using D-FAS Technology
- ER22-3298 Utilizing PFAS Aggregation at the Gas-Water Interface for Energy-Efficient PFAS Destruction
- ER21-5124 Low-Cost, Passive In Situ Treatment of PFAS-Impacted Groundwater Using Foam Fractionation In an Air Sparge Trench
- ER22-3438 Extraction and Removal of PFAS from Impacted Water and Soil using Air Bubbles
- ER22-3352 Cost-Effective Treatment of PFAS in Landfill Leachate Using Foam Fractionation
- ER22-3221 Gas Sparging Directly in Aquifers to Remove or Sequester PFAS
- ER23-7939 Sustainable On-Site Removal and Destruction of PFAS Using Surface Active Foam Fractionation and Supercritical Water Oxidation

12.2.4 In Situ Remediation with Colloidal Activated Carbon

Treatment Description: The primary function of injectable colloidal activated carbon (CAC) is to immobilize contaminants and prevent their further horizontal and vertical migration in groundwater. By flowing CAC into the flux zones of an aquifer, dissolved contaminants migrating in groundwater, as well as those contaminants back-diffusing from lower permeability zones, are captured and taken out of solution, thereby lowering the risk to downgradient receptors (for example, drinking water wells, surface water bodies). Long-term performance is subject to various parameters, such as contaminant flux and media saturation, similar to GAC.

CAC may be injected in situ using a grid pattern in source zones to immobilize contaminants, or it may be injected in a transect pattern perpendicular to the width of a plume to mitigate contaminant flux. Direct push or vertical wells can be used to inject CAC into the subsurface (McGregor 2020).

Treatment Mechanism: CAC consists of colloidal-sized particles of activated carbon (2 microns diameter on average) in aqueous suspension (the consistency of black-colored water), which can flow into aquifer flux zones upon gravity-feed or low-pressure injection. After injection, CAC particles will attach strongly to the aquifer matrix, where they can act as passive sorbents for organic contaminants, including PFAS. This sorption mechanism is detailed in Section 12.2.1. Due to the small size of the particles, the kinetics of PFAS sorption on colloidal carbon are much faster than can be achieved with GAC, resulting in higher removal efficiencies (Xiao et al. 2017).

Unlike larger powdered activated carbon (PAC) particles (50+ micron diameter), CAC particles are small enough to move through most aquifer material pore throats under low pressure, allowing for relatively even distribution within aquifer materials. McGregor (2020) demonstrated that trying to inject PAC was not as successful as injecting CAC because higher injection pressures were required, resulting in preferential PAC distribution in more permeable lenses of sand. McGregor (2020) also observed preferential accumulation of PAC within the sand packs of monitoring wells that were present at the time of injection at four sites, which would lead to false positive treatment results. CAC accumulation was not observed in the sand packs of the monitoring wells.

State of Development: Over the past decade, in situ CAC treatment technology has been well established with project sites contaminated with hydrocarbon and chlorinated solvent contaminants. The application of the technology to treat PFAS contamination in groundwater has been successfully employed on >25 project sites in North America, Europe, the Middle East, and Asia (for example, McGregor 2020; Carey et al. 2022). A case study is included in Section 15.2.3, which details a full-scale CAC project site to predict the theoretical longevity and performance of the CAC to treat PFAS in groundwater in the presence of hydrocarbons. Results indicated an anticipated longevity of successful PFAS treatment on the order of decades. The study noted that longevity of performance could be extended by increasing the CAC dose, by increasing the thickness of the treatment zone perpendicular to flow, or by additional injection upon any future PFAS breakthrough.

Effectiveness: McGregor (2018) discussed the in situ injection of CAC at a site in central Canada to mitigate mass flux of PFOS and PFOA from a fire training area source zone. Prior to CAC injection, PFOS and PFOA were measured in groundwater monitoring wells at concentrations up to 1,450 ng/L and 3,260 ng/L, respectively. Monitoring wells at the site were screened in a shallow, thin silty sand overburden unit at depths of approximately 5–10 feet below ground surface. CAC was injected into the source zone at low pressure through temporary wells installed using direct push technology. Postinjection core sampling indicated that CAC was measured at distances of up to approximately 15–20 feet from the injection wells. Carey et al. (2022) discussed the performance of this project site where no detections of PFAS in the CAC adsorption zone were detected over the first 5 years (10 sampling events) except for a single well where low detection of PFOS and PFUnA at 533 days was seen (but not reproduced). The first five monitoring events included analysis for only PFOS and PFOA. The last six monitoring events included analysis for a full suite of PFAAs. At event 11 (the 6-year point), the detection limits were lowered to 1 ng/L and several PFAS were observed slightly above the new detection limits.

Carey et al. (2022) presented performance data on 16 field-scale projects employing CAC to treat PFAS in groundwater. On nine of the sites PFAS have been reduced to concentrations at or below detection levels, including five projects that analyzed for both short- and long-chain PFAS. Another five project sites showed >90% reduction in PFAS constituents, while one site showed >80% reduction. On a site where treatment of PFAS in groundwater was attempted near a landfill, initial results indicated >91% reduction but were not sustained, presumably due to the high dissolved organic load (>20 mg/L) associated with commingled landfill leachate.

Design Considerations: The focus of a CAC treatment is to target the actual vertical zone in the subsurface carrying the PFAS contamination rather than simply treating a broad vertical section of aquifer, as is often the case with pumping systems. This targeting of the vertical PFAS flux zone allows for a more accurate interception of the PFAS mass requiring treatment and usually results in a much lower cost of treatment. The use of direct-push injection or dedicated injection wells targeting these flux zones allows for accurate application of the CAC suspension.

The longevity of any CAC treatment performance will be dependent upon PFAS composition, rates of PFAS mass discharge, presence of co-contaminants, CAC dosing, and CAC application design. Carey et al. (2019) performed modeling with respect to an actual full-scale CAC project site to predict the theoretical longevity and performance of the CAC to treat PFAS in groundwater in the presence of hydrocarbons. Results indicated an anticipated longevity of successful PFAS treatment on the order of decades. The study noted that longevity of performance could be extended by increasing the CAC dose, by increasing the thickness of the treatment zone perpendicular to flow, or by additional injection upon any future PFAS breakthrough.

Sustainability: The environmental footprint of in situ CAC treatment is relatively small when compared to treatment technologies requiring pumping of groundwater and aboveground separation of contaminants, hauling of waste, and then destruction of collected waste. CAC operates passively. Use of CAC avoids on-going energy requirements and greenhouse gas associated with operation and maintenance of pump and treat systems.

The Danish EPA (2022) performed a sustainable remediation methodology assessment (ISO 2017) generating a comparative full life cycle analysis (LCA) on the use of a commercially available CAC product, and pump and treat technology for treating groundwater contaminants. Results showed that over a 30-year operating period, the CAC treatment generated less than 5% of the greenhouse gases generated using the pump and treat approach. Although the actual site chosen for comparison in the study was treating trichloroethylene contamination, the comparative LCA results may provide information about the sustainability of the CAC treatment approach relative to pump and treat approaches for carbon-sorptive dissolved organic contaminants.

Related Past, Ongoing, and Recent Research Funded by SERDP (ER)

- ER20-5100 In Situ PFAS Sequestration in AFFF-Impacted Groundwater
- ER20-5182 Validation of Colloidal Activated Carbon for Preventing the Migration of PFAS in Groundwater
- ER21-1070 Hydraulic, Chemical, and Microbiological Effects on the Performance of In-Situ Activated Cardon Sorptive Barrier for PFAS Remediation in Coastal Sites

12.3 Field-Implemented Solids Treatment Technologies

Field-implemented technologies are those that have been implemented in the field by multiple parties at multiple sites and have widespread regulatory approval, and the results have been documented well in the peer-reviewed literature. The technologies in this section may be applied to a variety of PFAS-impacted solid media, including soil, sediments, or sludge.

One unique class of solid waste that may require treatment is biosolids generated by wastewater treatment plants, which have been historically managed through land application, use or disposal at landfills, or incineration. These technology options have not been fully evaluated to determine their effectiveness for PFAS in field-implemented examples. The regulatory landscape for management of biosolids is evolving, and some states have started to require testing. A few prohibit land application if concentrations of certain PFAS are greater than specific levels. (see Section 12.1.4.3)

Site-specific evaluation is always needed to identify the best technology for a given treatment scenario. As with water treatment, solids treatment can be performed ex situ (for example, excavation or dredging) or in situ (for example, injection or reactive capping). At present, field-implemented solids treatment has been performed almost entirely ex situ. There are currently three known field-implemented technologies for treating soil contaminated with PFAS: sorption/stabilization, excavation/disposal, and soil washing.

12.3.1 Sorption and Stabilization

Treatment Description: Amendments are added to the soil and sediment to reduce the potential for PFAS to mobilize from soil and sediment to groundwater and surface water. For sorption purposes, PFAS-adsorbing materials (for example, activated carbon) can be applied through in situ soil mixing or ex situ stabilization (for example, pug mill mixing) to reduce the leachability of PFAS from contaminated soil/sediment through physical and/or chemical bonding.
Sorption and stabilization (considered "immobilization" or "chemical fixation" technologies) is a relatively quick, simple, and low-cost (relative to off-site disposal) way to reduce ongoing PFAS contamination transport to waterways and groundwater from source zones. The main disadvantage is that these technologies do not destroy the contaminants, but rather bind or immobilize them. For some amendments, established test methods have shown the binding to be stable over the long-term (see below).

Stabilizing PFAS in situ may reduce the effectiveness of future in situ soil treatments and thus limit future remediation to excavation and disposal to landfill or in situ remediation employing strong chemicals and/or high energy inputs to overcome stabilization bonds. Long-term project objectives should be carefully evaluated before implementing any technology that could limit future options. Additionally, in flood-prone areas, immobilized/stabilized soils with PFAS could be eroded and transported off site.

Treatment Mechanism: Amendments adsorb or stabilize PFAS to reduce their release from soil. This occurs primarily through electrostatic interactions between charges on the PFAS functional group and charges on the sorbent, as well as hydrophobic interactions between the amendment and the carbon-fluorine chain on the PFAS. "Principal component analysis" has shown "that electrostatic sorption dominates for shorter chained PFAS and that hydrophobic sorption dominates for longer chained PFAS" (Sörengård et al. 2020). Typical amendments that have been demonstrated in the field include activated carbon and activated carbon-composite materials, such as activated carbon blended with aluminum hydroxide, kaolin, and carbon. Some of these blends are said to be specifically designed to treat anionic, cationic, and zwitterionic long- and short-chain PFAS (Kempisty, Xing, and Racz 2018).

State of Development: Sorption and stabilization techniques using carbon-based amendments are considered field-implemented technologies. Various amendments have been applied to soil/sediment both in situ and ex situ. Different delivery methods for amendments, such as injection or in situ mixing (ISM), may provide different results depending on geology and objectives. Proprietary formulations of activated carbon with inorganic amendments have been developed with the intent of increasing their sorption of PFAS. One such product was used on a large-scale project involving the ex situ treatment of 900 tons of PFAS-impacted soil from an airport site in Australia (Stewart 2017). However, controlled third-party laboratory studies (Sörengård et al. 2020) and field tests (USEPA 2017) have shown little advantage to these formulations when compared to powdered activated carbon alone. Additional studies have been performed looking at biochar (Zhang and Liang 2022) and fly ash (Sörengård et al. 2022), with mixed results.

Effectiveness: Sorption and stabilization techniques vary in their effectiveness according to site conditions, PFAS types, mixing approaches, and amendments chosen.

The effectiveness of 44 different sorption amendments to treat a wide range of PFAS was studied and summarized in a detailed and controlled series of experiments (Sörengård et al. 2020). The study included three forms of powdered activated carbon, a commercial proprietary blend of carbon and minerals, granular activated carbon, biochars, and a number of other sorbents. Results showed the powdered activated carbon amendments outperformed all other amendments in sorbing PFAS in all PFAS groups measured (short-chain C3–C7 PFCAs, long-chain C8–C17 PFCAs, and PFSAs, FTSAs, and FOSA).

A study conducted with an activated carbon-based blend amended with inorganic minerals showed that at average addition rates of around 2.5–5% (wt/wt), PFOS and PFOA in soil leachates were reduced by 95% to >99% following a 48-hour treatment process (Stewart and MacFarland 2017).

The charge on the PFAS affects sorption (for example, cations sorb more readily than zwitterions and anions). Aquifer and soil chemistry also affect the sorptive ability of PFAS onto the amendments. High organic content in soil can reduce effectiveness (NGWA 2017). Low pH, the presence of polyvalent cations in the soil, or treatment amendment also increases sorption, retardation, and metals precipitation. An independent study at the University of Adelaide, Australia, showed that environmental ranges of pH and ionic strength did not adversely affect the binding of a specialized amendment to PFOA

(Lath et al. 2018). Co-contaminants also play a role in the effectiveness of PFAS sorption. A recent review article (Li, Oliver, and Kookana 2018) showed that the organic carbon component of natural soils and sediments plays less of a role in PFAS sorption than once thought; the mineral component of the soil/sediment and the pH conditions play a more important role in PFAS adsorption.

In independent studies, the Multiple Extraction Procedure (MEP; USEPA Method 1320; USEPA 1986) has been used to successfully demonstrate the simulated long-term stability of immobilized PFAS in amended soils (Stewart and MacFarland 2017). The MEP is designed to simulate 1,000 years of acid rain conditions in an improperly designed sanitary landfill. In another independent study, the accumulation of PFAS in earthworms and plants was reduced by >90% in soil treated by carbon-based immobilization compared to untreated soils (Bräunig 2016; Kempisty, Xing, and Racz 2018). The amended soil can be mixed with concrete and other stabilizers to improve performance; however, the concrete increases pH and may influence binder performance (Ross et al. 2018).

Design/Operating Considerations: To establish design and application parameters for implementation of sorption and stabilization technology in soils, it is necessary to perform site-specific laboratory and/or pilot treatability tests. Information and quantity of amendment material required (dose rates) for materials can be determined with either simple beaker or jar-type lab treatability tests. These studies are most applicable if site soils and water are used to ensure that the effects of site-specific geochemical characteristics are assessed. Once the dose of amendment material is determined, field pilot studies are often conducted to validate lab data and design for full-scale implementation.

For in situ soil mixing, the amendments are added to soils at the design dose or application rate under controlled conditions with specific types of equipment designed to perform mixing. In situ soil mixing can be performed on soils in place with a wide range of standard construction equipment, including excavators, large diameter augers, and in situ blenders. In addition to in situ soil mixing, soils can be removed and mixed in equipment such as a pug mill or other similar mixing systems. As for other contaminants that have been stabilized in projects executed over the past 30 years, the thoroughness of the mixing can impact performance of PFAS-specific stabilizing agents.

After implementation of in situ soil mixing, it is important to perform postconstruction quality assurance and quality control to verify design endpoints. This may include leachability (Toxicity Characteristic Leaching Procedure (TCLP), USEPA Method 1311(USEPA 2021); Synthetic Precipitation Leaching Procedure (SPLP), USEPA Method 1312(USEPA 2021); or Multiple Extraction Procedure (MEP), USEPA Method 1320(USEPA 2021)), hydraulic conductivity (ASTM D5084, ASTM 2016), and strength tests (various). ITRC has prepared a technical and regulatory guidance document on the development of performance specifications for solidification/stabilization (ITRC 2011) that may prove useful in planning a PFAS soil stabilization/solidification project.

Sustainability: The environmental footprint for sorption and stabilization includes emissions from earthwork equipment, manufacturing, and transporting amendment material. This footprint can be smaller than excavation if the treated soil is reused on site. Community impacts include hindrance of redevelopment due to land use restrictions. However, if the land use is not expected to change, such as on active government-owned aviation or military sites, stabilization with amendments and reuse of the soil may be a viable and cost-effective approach. If PFAS regulations change in the future, which is likely, reusing the PFAS-impacted soil could expose a facility owner to future liability.

Resources are available for performing a sustainability assessment for sorption and stabilization remedial design, relating to other contaminants (Goldenberg and Reddy 2014; Hou et al. 2016; Kuykendall and McMullan 2014).

Related Past, Ongoing, and Recent Research Funded by SERDP or ESTCP:

- ER22-3124 A New Concept of “Release-Capture-Destruction” to Enable Remediation of PFAS in Source Zone Soils
- ER22-3194 Green Remediation of PFAS in Soil and Water
- ER22-7313 Management and Mitigation of PFAS Leaching from Concrete

12.3.2 Excavation and Disposal

Treatment Description: This approach involves removing contaminated soil/sediment for off-site disposal. The contaminated material is disposed of at a permitted landfill, then the excavated area is filled with clean backfill. Treatment with stabilizing agents can reduce PFAS leachability from excavated soils and should be considered prior to landfilling. Sometimes, excavated soil/sediment can be treated on site using the sorption and stability approach or thermal treatment (as discussed in the Sections 12.4 and 12.7.2) followed by soil reuse or off-site disposal.

Treatment Mechanism: This method is intended to remove PFAS from the source location. Transportation and disposal in a lined landfill is an option for excavated soil; however, leachate management should be a consideration at these facilities (see Section 12.1.4.2).

State of Development: Soil excavation and disposal is a well-demonstrated, proven technology. However, PFAS have been reported in landfill leachate (Lang et al. 2017), although the source for PFAS in leachate may be consumer product waste containing fluorochemicals. In some states, the leachate is not analyzed or regulated for PFAS. Disposal of PFAS waste to landfills potentially adds to the PFAS contaminant load in the landfill leachate. Some nonhazardous waste landfills do not accept PFAS waste.

Effectiveness: Excavation and disposal of PFAS-contaminated soil effectively removes a source area that may otherwise serve as a continuing source of groundwater contamination but does not result in destruction of the PFAS. Disposal of PFAS-impacted soils or wastes into unlined landfills should be avoided as unlined or improperly lined landfills can be sources of PFAS to the environment.

Design/Operating Considerations**:** Difficulties in finding landfills willing to accept the waste, coupled with rapidly changing regulations regarding whether PFAS are hazardous or not, make this option less straightforward than one would expect. Case-by-case inquiries to landfill facility owners is likely the best course of action. Overall, issues related to disposal of PFAS in landfills are similar to issues commonly encountered with other contaminants. See Section 2.6.3, Solid Waste Management, for additional discussion on this topic.

Sustainability: The environmental footprint for excavation and disposal includes earth-moving equipment emissions, transporting contaminated soil and backfill, and resource extraction (such as borrow area fill material) of backfill material.

Truck hauling traffic affects the local community by creating additional traffic congestion, noise, and particulate matter emissions. The cost for this approach is high, but the solution is generally permanent and for smaller treatment volumes may be cost-competitive. Guidance is available for performing a sustainability assessment for an excavation and disposal remedial design (Cappuyns and Kessen 2013; Goldenberg and Reddy 2014; Söderqvist et al. 2015; Song et al. 2018).

12.3.3 Soil Washing

Treatment Description: Soil washing is generally considered a media transfer technology. It is an on-site, ex situ treatment process that uses physical separation and chemical desorption/extraction techniques to remove adsorbed PFAS mass from soil. Fundamentally, the application of soil washing systems relies on the principle that most environmental contaminants, with the propensity to interact with soil, will preferentially bind to the finer soil fraction (for example, clays and silts) versus the coarser grained soil fraction (for example, sands and gravels) (USEPA 1996). Soil washing systems use a wash solution usually consisting of water, but surfactant and/or an extraction solvent can also be used to dissolve and concentrate PFAS (ESTCP 2022). Physical size separation techniques are used to separate the finer grained from the coarser grained soil particles, thereby concentrating and reducing the PFAS-impacted soil volume that must be further treated or disposed. Refer to Figure 12-6 for a typical soil washing process schematic.

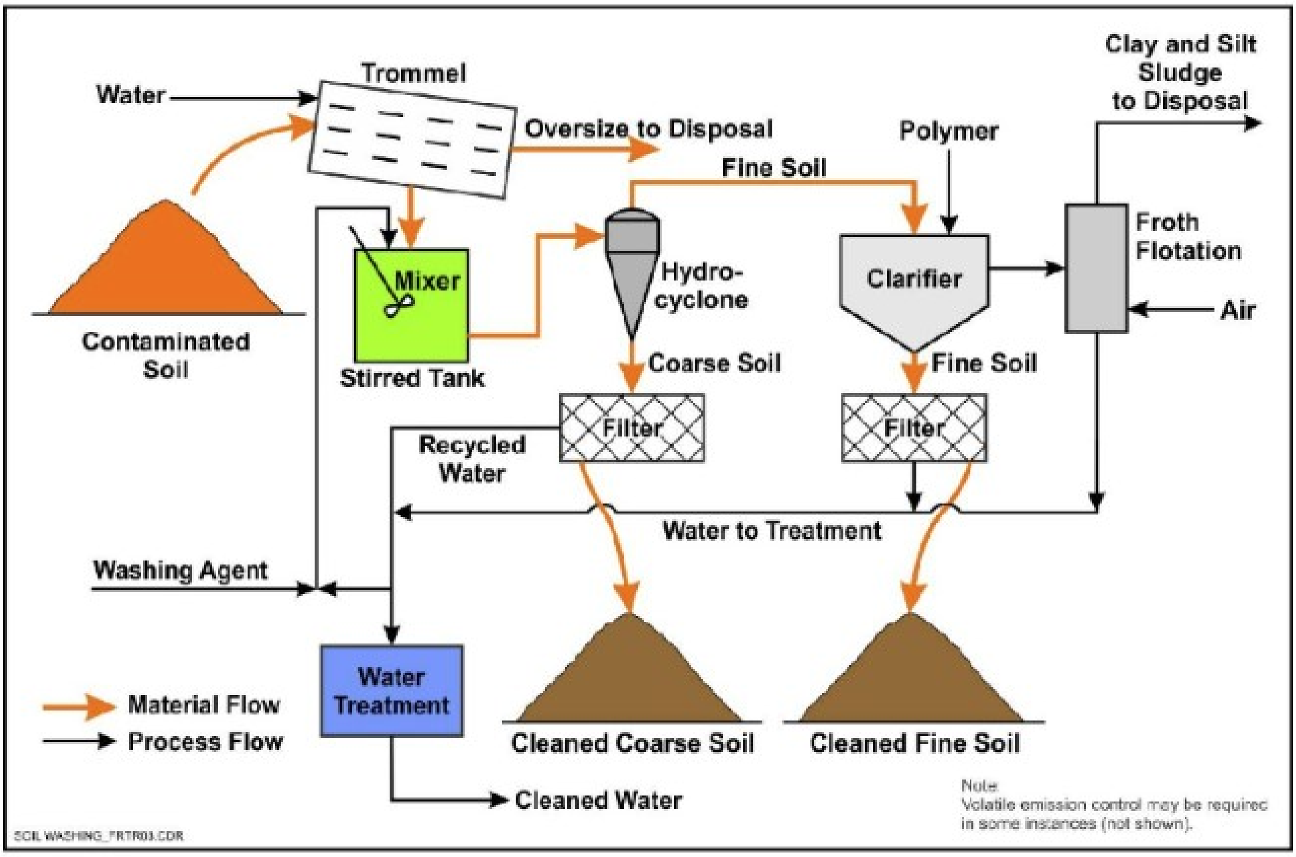


Figure 12-6. Soil washing process schematic.

Source: Federal Remediation Technologies Roundtable (https://www.frtr.gov/matrix/Soil-Washing/)

Treatment Mechanism: The concept of reducing PFAS soil contamination via particle size separation is underpinned by the preference of PFAS to sorb to soil fractions with high organic carbon content, promoting stronger hydrophobic interactions. Typically, finer soil fractions (for example, clays and silts) are enriched in organic carbon relative to coarser grained soil fractions (for example, sands and gravels). Therefore, using a fluid, such as water, to promote particle size separation can effectively segregate the soil fraction containing the highest PFAS impact. The PFAS impacted fine grained soil fraction can be further processed to minimize volume and managed separately for treatment or disposal from the coarser grained soil fraction. Several mechanical approaches can be implemented to facilitate the particle size separation process, including vibratory screens, trommels, hydrocylcones, and spiral classifiers (USEPA 1999).

During the soil washing process, the sorbed PFAS mass may transfer from the solid phase to the liquid phase through diffusion processes. Additionally, PFAS mass removal from impacted soil may be enhanced by promoting both desorption and dissolution into the liquid phase by flushing with water or an extraction solvent. PFAS extracted into the aqueous phase is then treated by other technologies (for example, GAC and/or IX) or staged for off-site disposal (ESTCP 2022). Leveraging desorption for PFAS mass reduction in impacted soil during the soil washing process is most effective for PFAS with lower distribution coefficients (i.e., less preference for the solid phase) and higher solubility in the wash solution.

State of Development: Soil washing is considered a field-implemented technology based on its history with other contaminants and has been evaluated for PFAS treatment efficacy in multiple field tests. The technology grew out of mining industry operations and was modified for environmental applications during the 1990s. It has historically been applied to soils contaminated with metals, semivolatile organics, and PCBs/pesticides (USEPA 1999; USEPA 1993). The same soil particle size separation and dissolution wash processes employed for these historical contaminants have been transitioned for application to PFAS-impacted soils based on similar physical and mass transfer properties. The transference of these separation and removal processes has been verified for PFAS-impacted soils by field demonstration projects performed to date. PFAS soil washing pilot/field demonstration projects have been performed at multiple Australian and U.S. sites (Quinnan et al. 2022; ESTCP 2022; Becker 2022). There are currently only a small number of vendors offering ex situ soil washing for full-scale applications. Further research and field studies are still required for alternative surfactants/extraction solutions that can be employed to remove PFAS more effectively from the finer grained soil fraction.

Effectiveness: A general guideline for contaminant reductions by soil washing is 90%–95% for the coarser grained soil fraction, assuming particle size separation of the coarser grained soils and mass transfer to the liquid phase for follow-up treatment/removal.

Results from an ESTCP pilot test confirmed that coarser grained sand and gravel fractions met performance goals, while the finer grained fraction was segregated for later treatment or disposal. The grain size composition was approximately 30% gravel, 40% sands, and 30% fines. Approximately 180 tons of PFAS-impacted soil was treated. Baseline PFOS concentrations detected in composite samples representing combined particle sizes ranged between 3.9 and 740 µg/kg, while detected baseline total PFAS concentrations ranged between 5.38 and 874 µg/kg. PFOS removal efficiencies were generally highest in the gravel fraction (94.6%–98.1%), followed by the sand fraction (88.6%–96.1%), and the finer grained fraction (-7.7%–61.8%, where variability in the PFAS concentrations in the finer grained fraction is thought to have caused the negative removal efficiency). The removal efficiencies for total PFAS for the coarser grained fraction were generally higher than PFOS for each stockpile, indicating that the soil washing process was effective at removing other PFAS (Quinnan et al. 2022; ESTCP 2022).

Another field-scale soil washing demonstration investigated the treatment of approximately 573 cubic yards of PFAS-impacted loamy sandy soil and sediments. Baseline stockpile characterization for PFOS concentrations ranged between approximately 3,000 µg/kg and 12,000 µg/kg for the coarser and finer soil fractions, respectively. Following two rounds of soil washing treatment, the coarser grained soil fraction showed a PFOS reduction of 99% while the finer grain soils PFOS reduction was 89%. Because of the particle size separation, the total soil volume requiring off-site disposal was reduced by more than 90% (Becker 2022; ESTCP 2022).

Design/Operating Considerations: Determining the soil grain size distribution, as well as PFAS concentrations within the various grain size types, are the key design/operating considerations. Since soil particle size separation represents the primary PFAS removal/soil volume reduction mechanisms, soil washing is less cost-effective as the percentage of finer grained soils increases. A particle size distribution of 0.25–2 millimeters is considered optimal for soil washing, while <0.063 millimeters may not be viable, which correlates to <25% silts and clays considered optimal and >50% may not be viable (USEPA 1990; 1997). High clay content with corresponding high moisture levels poses a material handling and feed challenge. Heterogeneity and inconsistent feed conditions can also impact PFAS removal efficiency, which can require preprocessing for homogenization. Soils may need to be segregated by order of magnitude concentrations and treated using different process conditions to optimize treatment throughput and minimize treatment costs. Other key process parameters include soil throughput, retention time, contaminant solubility, wash solution to soil ratios, soil cation exchange capacity, and design parameters associated with the wash solution treatment and soil dewatering processes.

Sustainability: Intensive energy usage is required for the various material handling, separation, and liquids treatment operations. The generated wash solution requires treatment but can be recycled for continuous reuse. Treated soils can potentially be redeposited on site if applicable regulatory criteria are met, which avoids off-site disposal. Separated finer grained soils that do not meet regulatory criteria require off-site disposal.

Related Ongoing Research Funded by SERDP:

- ER20-5258 Ex Situ Soil Washing to Remove PFAS Adsorbed to Soils from Source Zones

12.4 Incineration

Because of the increasing interest in incineration from the public, press, and regulatory community, and the potential application of incineration to liquids or solids, the following information is being provided as a separate section.

Treatment Description: Incineration is defined as “burning hazardous materials at temperatures high enough to destroy the contaminants” (USEPA 2012). Incineration is destruction (mineralization) using combustion, which requires heat and oxygen. Heat is applied directly to the PFAS-contaminated solids (soil/sediment/spent adsorbents/waste) or liquids (AFFF/water/wastewater/leachate/chemicals). Vaporized combustion products can be captured (precipitation, wet scrubbing) and/or further oxidized at elevated temperature. Pyrolysis and gasification are related thermal treatment technologies. Some additional information about pyrolysis and gasification is discussed in Section 12.5, thermal treatment for air sources and in 12.7.2 thermal treatment for solids.

State of Development: Incineration is a mature technology that has been used for various solid and liquid wastes, but its ability to remove PFAS from waste streams is a topic of study. The USEPA has compiled a PFAS Thermal Treatment Database (USEPA 2022) to help synthesize the current body of research.

Effectiveness: Incineration is one of only a few technologies that can potentially destroy PFAS, though the ability to destroy PFAS is not well understood (USEPA 2020). In December 2020, USEPA released a draft interim guidance on destruction and disposal of PFAS (USEPA 2020). Recent testing and reporting of PFAS destruction by incineration has documented destruction efficiencies of greater than 99 percent for some PFAS (Barr Engineering 2022; Chemours 2023; EA Engineering 2021).

There are multiple areas of active research to evaluate the effectiveness of incineration which initially focused on destruction temperatures and treatment times. Ongoing research is also assessing the potential of incineration to generate byproducts of incomplete combustion, to analyze stack gas, to understand deposition onto land, and to manage incinerator wastes, along with other potential risk factors.

In April 2022, in response to a congressional requirement in the National Defense Authorization Act (NDAA), the Department of Defense (DOD) placed a temporary ban on incineration of PFAS-containing materials generated by the DOD up until such time as a PFAS disposal policy was developed consistent with USEPA (2020) and Section 343 of the 2022 NDAA. The DOD published a memo with interim guidance about destruction or disposal of materials containing PFAS, including AFFF that has been taken out of service, on July 11, 2023 (USDOD 2023). The DOD interim PFAS disposal guidance supersedes the previous temporary moratorium and is expected to be updated annually. USDOD (2023) identifies the following PFAS disposal options in order of prioritization: 1) Spent GAC reactivation at a RCRA permitted facility; 2) landfilling at a permitted RCRA Subtitle C hazardous waste facility; 3) landfilling at a permitted RCRA Subtitle D non-hazardous solid waste facility with an appropriate leachate and gas collection and management system; and 4) incineration at a permitted RCRA Subtitle C hazardous waste facility. Publicly available air testing results for PFAS incineration destruction efficiency and byproducts of incomplete combustion were considered in the development of the DOD interim PFAS disposal guidance, while ongoing future PFAS incineration air testing and research and updates to USEPA (2020) will be incorporated into the future annual updates. A follow-up statement was published on July 17, 2023 about additional planning and coordination that is needed before incineration is implemented (USDOD 2023).

Design/Operating Considerations: Waste incinerators are fixed facilities. Federal and state permits dictate the materials processed, core incinerator operations (for example, temperature and time, turbulence), and control of process air, liquid, and solid wastes. Permit and design/construction similarities reduce the operational and performance differences between individual incinerators.

When considering waste disposal options, transportation costs, energy costs, regulatory approvals, and final disposition of process waste residues should be evaluated, as these differ among incineration facilities.

Sustainability: The environmental footprint for incineration includes transportation and supplemental fuel for the incineration process. Incineration of contaminated soil, liquid wastes, and IDW is energy-intensive and PFAS emissions, including potential PFAS combustion byproducts, from incinerators are currently not well understood (USEPA 2020). Truck hauling traffic affects the local community by creating additional traffic congestion, noise, and particulate matter emissions. The cost for this approach is high, but the solution may be cost-competitive for smaller treatment volumes.

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER19-1408 Analysis of Fate of PFAS during Incineration
- ER22-7470 Development and Application of Injectable Fuels/Adjuncts for In Situ Treatment of PFAS and Co-Occurring Chemicals in Source Areas by Smoldering Combustion

12.5 Air Treatment Technologies

PFAS vapors or particles can be generated during any activity that involves PFAS or materials containing PFAS. The multitude of sources for PFAS-containing vapors and particles, some of which are unique due to their specific function (for example, industrial or commercial processes), is complicated by a lack of basic understanding of the chemical and physical properties for PFAS that are not used as widely. Additionally, air emissions should be considered as part of any PFAS-related activity, regardless of whether it is the primary media being treated. For example, during landfill leachate treatment, air emissions could be generated, requiring treatment.

PFAS vapors or particulates may be captured by conventional air pollution control (APC) equipment that has been historically developed to control vapors, particles, and fine dusts emitted from permanent industrial sources or temporary environmental or construction sites. Though the effectiveness of conventional APC technologies in removing PFAS from air streams is not well understood, current practice is to apply these methods and practices of vapor and dust control that are presently used or required for similar equipment and processes. The performance of these technologies should continue to be researched and documented with a focus on those PFAS that can be reliably quantified. Specific research needs for the emissions from thermal treatment technologies, including those related to APC equipment, are discussed in USEPA (2020, section 3.a).

A standardized method for stack testing for PFAS emissions has only recently been developed (see Section 11.1.7.12), and stack testing to date has primarily focused on the overall removal efficiency for the destruction technology being evaluated (for example, see Barr 2022). Sampling stack emissions and performing adequate analysis is an active area of research and will need to be a part of assessing adequate treatment of any stack emissions thought to contain PFAS. Additional information on the effectiveness of thermal treatment technologies is included in Section 12.7.2.

12.5.1 Conventional Air Pollution Control (APC) Technologies

PFAS vapors may be captured by conventional APC equipment. However, this does not mean that older methods do not need to be tested to document their performance, nor does it mean the older methods should not be modified or entirely redesigned to account for PFAS. Rather, it means that conventional APC technologies that can treat vapors and particles containing PFAS may have some level of removal efficiency and should be evaluated to ensure appropriate capture or destruction is taking place.

Thermal treatment technologies for PFAS contained in emissions are an area of focus in the research community. A limited number of these technologies have been implemented and are currently being evaluated for their efficiency.

Technologies and equipment for control of potential emissions can be placed in four groups: 1) those that capture PFAS-containing particles; 2) those that capture PFAS-containing vapors, 3) those that capture PFAS in both vapors or particles, and 4) those that destroy PFAS in the air stream being emitted from the process. Destruction of PFAS through thermal oxidation and incineration is briefly covered here and is also covered in Section 12.4. Particle capture and vapor capture are further described below. More information about specific air pollution control technologies is available from USEPA (2022), which is a web site with links to individual technology fact sheets.

12.5.1.1 Particle Capture

PFAS that are fully partitioned to particulate matter in the air stream could be removed by particle capture mechanisms:

- Bag houses and similar units rely on filter media whose pore openings are smaller than the smallest targeted particle or particulate. The nature of the targeted material is less important than its overall size and smallest dimension. The filter material may be configured as a bag or a sheet. Either may be flat or pleated to increase its surface area within a specific area perpendicular to the air flow.
- Cyclones accelerate the speed of a particle as it travels a circular path that continually decreases in diameter. As the same amount of air is forced through a smaller cross section, its velocity increases. The weight of a particle or particulate becomes the force that pushes it to the outer diameter of the spiral. A collection point in the design diverts the slice of total air flow containing all particles traveling along the outer wall to a collection vessel. This method generally works best when the air is relatively dry so that the solids do not adhere to the walls of the cyclone.
- Wet scrubbers add a liquid (typically water) to the air stream being treated. They are used to control airborne vapor and particles. There are two main reasons for the addition of water:
    - Water adsorbs to the particle to increase its weight and accelerate its settling under the force of gravity. The air flow is often horizontal to the unit, and the cross-section of the wet scrubber increases greatly (at least an order of magnitude) immediately after the point where the liquid is introduced.
    - Water in the liquid droplets, mist, or fine spray provides enormous area through which water-soluble or miscible vapors may dissolve. The rapidity of this transformation is important because the time the air stream is exposed to water droplets or vapors are in contact with the air stream is typically very limited.
        - Wet-scrubber air often flows horizontally to allow more volume or area for the particles to fall or settle.
        - Wet scrubbers (or scrubber towers) through which air travels vertically and is discharged at the top often employs a greater mass or volume of water to a given mass of particles

or vapors than a horizontal configuration. This provides more water particle surface area and higher humidity, which improves capture of vapors and/or particles.

- Electrostatic precipitators (ESPs) contain one or more grids of fine wires perpendicular to the air flow. Electrical current applied to the grids creates a small, opposite charge on particles in the air or changes the charge on individual particles. These charges are intended to enhance the capture of particles on the charged grids and potentially other surfaces of the unit. Low humidity in the air to be treated is desirable.

12.5.1.2 Vapor Capture

APC technologies that specifically target vapors are few, though the use of various media allows capture of specific contaminants or mixtures of contaminants better than on one medium. The most common vapor treatment technique is adsorption of vapors, which may contain PFAS, from the treated airstream onto media. Media may include granular activated carbon, raw or coated clays, or synthetic resin. Some media may capture numerous PFAS while others perform better for groups (for example, short- or long-chain compounds or those with specific subgroups). The evaluation of the efficiency of these technologies depends on important operating conditions such as the empty-bed contact time (EBCT), which can vary for each media type. Typical vapor control EBCTs range from seconds to a minute. Very fine (powdered) dry media can be injected into the air stream in special cases. However, the practice is unusual in environmental remediation and creates an additional waste stream (that is, the powdered media) that must be managed. These technologies will require continued evaluation and ongoing research to ensure that the objectives for PFAS removal in the air stream are adequate.

12.5.1.3 Thermal Treatment

The use of thermal treatment for PFAS destruction in stack emissions is a topic of current research and is dependent on having reliable methods for sample collection and analysis of PFAS contained in those emissions. Pyrolysis, gasification (see Section 12.7.2), and thermal oxidation are being investigated for their use and efficiency on PFAS-laden air streams. Some investigations have shown significant levels of PFAS removal using these methods (Winchell 2022; Chemours 2020; Barr 2022). Continued data collection on the efficiency of these systems will guide this important management option to control PFAS in stack emissions in the future.

12.6 Limited Application and Developing Liquids Treatment Technologies

The treatment technologies presented in this document are provided in a hierarchy defined in Section 12.1, which is based on level of implementation and confidence derived from widespread, well documented examples. The three development levels are: field-implemented technologies, limited application technologies, and developing technologies. Both in situ and ex situ technologies are included in this section. It is not always clear if a limited application or developing technology may be effective in situ, ex situ, or both; therefore, further distinction is not made in this section.

The field-implemented technologies described in the preceding sections have been applied at multiple sites and are well documented in the available literature. In addition to these well-demonstrated technologies, many technology approaches have been tested in academic and other research laboratories at the bench scale or have progressed as far as field pilot tests or limited field applications. These limited application technologies are briefly summarized in the Table 12-1 Treatment Methods Table Excel File. Additional information is provided in the following sections.

Not all of these limited or developing technologies have been demonstrated as suitable or effective under multiple treatment scenarios. For instance, destructive technologies, such as electrochemical oxidation, nonthermal plasma, hydrothermal alkaline treatment, and supercritical water oxidation, have been shown to be effective for treatment of high concentration, low volume liquids but may be less suitable for high volume, low concentration liquids.

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER18-1026 Rational Design and Implementation of Novel Polymer Adsorbents for Selective Uptake of Per- and Polyfluoroalkyl Substances from Groundwater
- ER18-1515 Cost-Effective Destruction of Per- and Polyfluoroalkyl Substances from DoD Subsurface Investigation-Derived Wastes using a New Class of Adsorptive Photocatalysts
- ER18-1417 Molecular Design of Effective and Versatile Adsorbents for Ex Situ Treatment of AFFF-Impacted Groundwater
- ER18-1395 Electrically Assisted Sorption and Desorption of Per- and Polyfluoroalkyl Substances
- ER18-1052 Remediation of Per- and Polyfluoroalkyl Impacted Groundwater Using Cationic Hydrophobic Polymers as Ultra-High Affinity Sorbents

- ER21-1018 Destruction of PFAS by Hydrodynamic Cavitation

12.6.1 Sorption Technologies

12.6.1.1 Coated Sand

Polymer-coated sand is an adsorbent material that has high affinity for organic contaminants. Cyclodextrin molecules are polymerized by a cross-linking agent and form inclusion complexes with many organics. The adsorbent material has two components: (a) polymer coat (active component that removes the contaminants) and (b) support base (inactive component); the combination of both provides an adsorbent with high selectivity and mechanical stability.

The adsorbent showed similar performance in removing PFOA and PFOS as GAC, but one of the key features of this technology is the high regenerability of the adsorbent (filter) for reuse (Bhattarai, Manickavachagam, and Suri 2014). Another important feature of the technology is that it can remove other organic pollutants such as chlorinated solvents (for example, trichloroethene (TCE), perchloroethylene (PCE), hexavalent chromium, and others (Badruddoza, Bhattarai, and Suri 2017). Surface modification has been shown to improve the adsorption of PFOS (Zhou, Pan, and Zhang 2013) by using organic polymeric surfactants.

Related Ongoing Research Funded by SERDP

- ER20-5100 In Situ PFAS Sequestration in AFFF-Impacted Groundwater
- ER20-5182 Validation of Colloidal Activated Carbon for Preventing the Migration of PFAS in Groundwater

12.6.1.2 Zeolites/Clay Minerals (Natural or Surface-Modified)

Zeolites are naturally occurring aluminosilicate compounds that are widely used in chemical separation and purification due to their high surface area and small uniform pore size among other properties (Tao et al. 2006). Zeolites are also being increasingly considered as a medium for the sorption of various pollutants, including cationic heavy metals, ammonium, and some volatile organic compounds, due to the aforementioned properties, as well as their high ion exchange capacity and low cost (Delkash, Ebrazi Bakhshayesh, and Kazemian 2015). Clay minerals, including natural and surface-modified (see below), are also used as adsorbents and are similar to zeolites in composition but have different crystalline or chemical structure. Surface-modified clays have been reported to have enhanced adsorption performance for a variety of organic and inorganic constituents (Han et al. 2019), as well as for PFAS (Zhou et al. 2010, 2013).

Both zeolites and clay minerals can be used ex situ (that is, pump and treat) by being placed in packed-bed flow-through vessels or in situ via injection into aquifers. In situ applications of these materials are lacking in study or field application. Most available literature is limited to academic laboratory experiments (Ochoa-Herrera and Sierra-Alvarez 2008; Punyapalakul et al. 2013; Zhou, Pan, and Zhang 2013; Zhou et al. 2010). Du et al. (2014) and Arias Espana, Mallavarapu, and Naidu (2015) provided comprehensive literature reviews.
Zeolite and clay minerals use both ion exchange and adsorption mechanisms to remove PFAS from water. These materials exhibit widely varying PFOS and PFOA adsorption capacities (Du et al. 2014), so PFAS adsorption performance should be assessed for each specific zeolite or clay-based media. However, synthetic processing of zeolite can create highly siliceous material (Baerlocher 2007) or can incorporate cationic surfactants into the surface structure (aka surface-modified zeolites–SMZ) (Jiménez-Castañeda and Medina 2017). One study indicated that engineered zeolites with a high Si/Al ratio were effective at adsorption of PFOS, presumably due to hydrophobic interactions rather than ion exchange (Ochoa-Herrera and Sierra-Alvarez 2008).

Surface-modified clays are made by intercalating a modification agent into the clay that has a high affinity for specific classes of contaminants. For PFAS adsorption, the modification agent is attached to the clay via cation exchange sites and includes electrostatic and hydrophobic moieties that are highly specific for PFAS. Mechanistically, PFAS molecules diffuse into the interlayer space of the surface-modified clay and then are bound through ionic and van der Waals forces with the fixed modification agent (Yan et al. 2021).

Two modified clay-based adsorbent products are identified as being used in field pilots or small-scale field trial applications (Arias et al. 2013; Arias Espana, Mallavarapu, and Naidu 2015) to treat PFOA and/or PFOS.

A commercially available surface-modified clay was successful at adsorbing a variety of PFAS from AFFF-impacted groundwater. The media was resistant to fouling by groundwater constituents, such as natural organic matter, and common co-contaminants (diesel, TCE, and 1,4-dioxane) (Yan et al. 2020). Laboratory and pilot-scale column testing of surface-modified clay for PFAS removal from contaminated groundwater that is to be used for drinking water showed PFOS and PFOA removal to the treatment target (2 ng/L). This media demonstrated a shorter empty bed contact time (EBCT) and longer media bed life than 13 other adsorbents (Pannu and Plumlee 2021; Hwang and Grieco 2021). PFAS adsorption (short- and long-chain) by using surface-modified clay with a variety of water types was examined in Grieco et al. (2021) and Najm et al. (2021).

High silica materials, such as H-form synthetic mordenite (HSM) and Y-form sodium zeolite (NA-Y80), and hydrotalcite clay provided adsorption capacities that were equivalent or exceeded powdered activated carbon (PAC). Surfactant-modified clays also performed as well as or better than PAC. It should be noted that none of these studies were conducted in flow-through column experiments, so applicability to ex situ treatment systems cannot be assessed. Arias Espana, Mallavarapu, and Naidu (2015) stated that organoclays, clay minerals, and highly siliceous materials have fast kinetics (0.4–3 hr to reach equilibrium), making them suitable for remediation applications.

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER18-1526 Complete Reductive Defluorination of Poly- and Perfluoroalkyl Substances (PFASs) by Hydrated Electrons Generated from 3-Indole-acetic-acid in Chitosan-modified Montmorillonite
- ER21-1238 Sustainable PFAS Treatment Using Layered Double Hydroxide (LDH) Sorbents
- ER22-7482 Demonstration-scale Evaluation of a Novel Surface-modified Clay Adsorbent: Comparison of Fluoro-Sorb, GAC, and IX Resin for the Removal of PFAS and Co-Contaminants in Groundwater

12.6.1.3 Biochar

Biochar is a hybrid word rooted in the words “biomass” and “charcoal.” Biochar is a carbon-rich porous solid that is synthesized by heating biomass, such as wood or manure, in a low oxygen environment (Ahmad et al. 2014). Biochar may be produced by pyrolysis of PFAS-impacted media (Thoma et al. 2021). This material has primary applications for carbon sequestration, improvement of soil fertility, and most recently as an adsorbent for pollutant removal. Biochar is characterized to have high affinity for organic contaminants, which is dependent on both the pore structure and the surface functional groups of the biochar material (Guo et al. 2017).Some of the key factors controlling the properties of biochar (for example, pore size composition and hydrophobicity) include the temperature of pyrolysis and biomass feedstock, among others. In many respects, the properties of biochar are similar to but generally lower than those of GAC for sorptive purposes.The variability of biochar with regard to performance parameters and quality control makes it challenging to implement on a large scale, and procuring large volumes of consistent materials and meeting design specifications can be challenging at large scales.

The available literature is limited to academic laboratory batch experiments on the bench-scale (Chen et al. 2011; Inyang and Dickenson 2017; Kupryianchyk et al. 2016; Rahman et al. 2014; Xiao, Ulrich, et al. 2017), with one published study reporting pilot-scale column operation (Inyang and Dickenson 2017).

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER22-3150 Engineering an “All-in-One” Biochar-Surfactant System for Enhanced PFAS Sorption and Reductive Degradation Using a Coupled Ultraviolet and Ultrasonication Approach
- ER22-3157 Hydrothermal Destruction of Per- and Polyfluoroalkyl Substances during Designer Biochar Reactivation
- ER23-3593 Tailored Carbonaceous Materials as Biofilter Amendments for PFAS Removal in Stormwater Runoff

12.6.1.4 Hydrogels and Fluorogels

Efficient removal of short-chain PFAS from water can be achieved using hydrogels and fluorogels because of their high selectivity and affinity for these compounds (Ateia et al. 2019; Kumarasamy et al. 2020). For example, Ateia et al. (2019) demonstrated selective, rapid removal of 16 PFAS using cationic polymer (hydrogel) poly (N-[3-(dimethylamino)propyl] acrylamide, methyl chloride quaternary (DMAPPAA-Q). While adsorption was not reversed in a standard environmental matrix, regeneration was possible using a simple solvent/salt matrix. Performance was maintained in six consecutive sorption/regeneration cycles.

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER22-3415 Novel Swellable Ionomers for Enhanced PFAS Sorption and Destruction

- ER22-3155 In situ Sequestration of PFAS from Impacted Groundwater Using Injectable High Affinity Cationic Hydrophonic Polymers

12.6.2 Precipitation/Coagulation/Flocculation

Precipitation/coagulation/flocculation is a common pretreatment approach used in wastewater treatment plants for removing various particles and dissolved constituents. Coagulants, either commodity or proprietary chemicals, can be added to water (conventional technology) or generated by anode-cathode reactions of metal plates inserted into the water (electrocoagulation). Common examples include:

- inorganic cationic coagulants (for example, alum, iron-based)
- commodity (for example, polyDADMAC) and specialty (for example, Perfluorad) polymers
- electrochemical precipitation

Coagulants assist in the formation of solids. Flocculation is typically conducted by adding a soluble polymer and slowly mixing to allow the particles to agglomerate and grow. Upon solid formation, constituents such as PFAS can be physically incorporated into, or sorbed onto, the flocculated particulate (which is known as co-precipitation). The precipitated solids are then separated from the water by sedimentation and/or filtration processes. The solid material containing the PFAS requires disposal, see the Table 12-1 Treatment Methods Table Excel File and Section 12.3.2.

Literature documents only bench-scale study results on treating PFAS via precipitation, flocculation, or coagulation; therefore, this is considered a partially developed technology. Evaluations have focused on conventional commodity chemical coagulation (for example, aluminum or ferric salts) and nonconventional coagulation (for example, proprietary chemical coagulants or electrocoagulation). Pilot- and full-scale applications have not been documented in the United States (Birk 2017), and specialty materials for PFAS applications will require strict quality control to ensure that performance characteristics are consistent.

Nonconventional precipitation (for example, electrocoagulation or advanced chemical precipitants) has shown more potential for direct PFAS treatment, but has very limited data. High-affinity cyclodextrin polymer has been tested in bench-scale reactors and was found to have superior removal capacity to GAC (Xiao, Ling, et al. 2017).

Electrocoagulation reactors, which range from basic to very sophisticated designs, have been reported to be highly efficient, compact, relatively low cost, and completely automatable (Baudequin et al. 2011; Lin et al. 2015). Recent studies have found that PFAAs, such as PFOA and PFOS, can be quickly sorbed on the surface of zinc hydroxide particulates generated by electrocoagulation (Lin et al. 2015).

Related Past, Ongoing, and Recent Research Funded by SERDP or ESTCP:

- ER-2425 Development of a Novel Approach for In Situ Remediation of PFC-Contaminated Groundwater Systems
- ER18-1026 Rational Design and Implementation of Novel Polymer Adsorbents for Selective Uptake of PFASs from Groundwater
- ER20-5370 Sustainable Firefighting System Cleanout and Rinsate Treatment Using PerfluorAd®
- ER22-3194 Green Remediation of PFAS in Soil and Water

12.6.3 Redox Manipulation

Redox manipulation includes chemical oxidation and reduction technologies. These have been summarized in more detail in Nzeribe et al. (2019). Chemical oxidation for PFAS is a technology approach that is achieved via the delivery of liquid, slurry, or gaseous oxidants to transfer electrons from a reactive oxidant species to a target (PFAS) and affect the cleavage of atoms in the PFAS molecular structure. Carboxylic or sulfonic group “heads” (functional groups) of PFAS are commonly more susceptible to redox transformation than the fluorinated carbon chain “tails.” There is a lack of robust evidence of defluorination via chemical oxidation processes. The mechanisms involving multiple species of free radicals that trigger PFAS oxidation are not well understood. PFAA precursors are also known to be oxidized to form persistent and terminal PFAAs without further oxidation (Houtz and Sedlak 2012; Anumol et al. 2016). Consequently, care should be taken to monitor site and plume conditions and understand potential formation and transport of transformation products.

Additional mechanistic studies are needed to develop chemical oxidation as a feasible PFAS remediation approach and to further assess factors that may promote or limit this technology. Common oxidants that have been documented to treat

PFAS and other organic contaminants (for example, chlorinated solvents) include ozone, catalyzed hydrogen peroxide, and persulfate, as discussed further below. The impacts of co-contaminants, quenching reactions, and metals mobilization are also considerations for redox-based remedies (for example, ITRC 2005, 2011).

12.6.3.1 Ozone-Based Systems

Ozone can be coupled with other oxidants such as hydrogen peroxide and persulfate to promote the generation of a suite of aggressive free radicals capable of degrading PFAS. An ozone-based system was implemented for the treatment of PFAS in a single field-scale test by Eberle, Ball, and Boving (2017) using combined ozone and activated persulfate.

The main pathway and mechanism behind the ozone-based system tested by Eberle, Ball, and Boving (2017) is unknown, as detailed mechanistic studies have not been performed. However, they suggested that PFAS reduction in groundwater after treatment was not limited to partial degradation, but it is possible that sorption also had a role to play in the declining aqueous PFAS concentration. They postulated that activated persulfate could lead to a decline in pH, thereby increasing sorption of PFAS to soil due to increased protonation.

This approach has been partially demonstrated in one field-scale setting, and results are encouraging for application using ex situ or in situ approaches. However, because there is an absence of supporting mechanistic data, it is likely that other factors could come into play that may promote or limit this technology.

The application of the ozone-based system for the treatment of PFAS has also been evaluated in bench studies (Lin et al. 2012; Kerfoot 2014; Huang et al. 2016; Eberle, Ball, and Boving 2017; Thomas et al. 2020). Lin et al. (2012) and Thomas et al. (2020) tested ozone systems without and inclusive of hydrogen peroxide addition in alkaline environments, and Kerfoot (2014) used hydrogen peroxide and ozone bubbles for a bench-scale test of groundwater from a monitoring well foam firefighting site in Canada. Huang et al. (2016)[598] combined ozone with photolysis to produce hydroxyl radicals and photogenerated electrons. Dai et al. (2019) tested combinations of ultraviolet light, ozone, and air fractionation, and reported that ozonated air fractionation provided more than 95% reduction in PFAS concentrations.

In the field demonstration, PFAS concentrations in groundwater were reduced by 21–79% after treatment. Also, an initial pilot test at a fire training area using ozone and peroxide has shown removal of 98.5% and 92.3% for PFOS and PFOA, respectively, in groundwater and over 80% for PFOS on saturated soil with proportional release of fluoride (Kerfoot 2016).

In bench-scale studies, Eberle, Ball, and Boving (2017) decreased PFAS by 99.9% using PFAS-contaminated site groundwater and spiked deionized water. Eberle, Ball, and Boving (2017) also reported that the system was not sensitive to other groundwater organics. Kerfoot (2014) reported 89.8% removal of PFOS and > 80% for other PFAS (PFPeA 89.8%, PFHxA 86.2%n and PFHxS 98.1%). These studies, however, do not confirm destruction through mass balance and analysis of byproducts.

Each of these approaches and test conditions used different water matrices and starting concentrations. It is difficult to state whether published regulatory levels can be achieved in practice with these technologies, but in general they appear to be effective as a polishing technology to achieve low part-per-trillion treatment requirements.

Related Ongoing Research Funded by SERDP:

- ER18-1545 Enhanced Oxidative Destruction of PFAS in Investigation-Derived Waste Soil and Water

12.6.3.2 Catalyzed Hydrogen Peroxide (CHP)–Based Systems

CHP is one of the strongest oxidant systems used in environmental remediation. It involves reaction of hydrogen peroxide with a catalyst to predominantly generate hydroxyl radicals. Some CHP systems produce nucleophiles and reductants, including superoxide and hydroperoxide (Mitchell et al. 2014). Common catalysts include transition metals such as iron (Fenton and Fenton-like reaction) or manganese, chelated metals, and naturally occurring minerals, for example, Watts et al. (2005) and Teel et al. (2007).

Hydroxyl radicals attack the alkyl groups of both PFCAs and PFSAs, but do not attack the perfluoroalkyl chain. As a result, PFCA and PFSA precursors are transformed to PFCAs of related perfluorinated chain length (Bruton and Sedlak 2017). Mitchell et al. (2014) demonstrated that superoxide and hydroperoxide (which are nucleophiles and reductants generated as a reaction in CHP but are not chemical oxidants) generated in alkaline pH CHP systems mineralize PFOA but did not elucidate a mechanism.

Bench-scale testing has been successfully demonstrated. Field deployment of hydroxyl radical-based CHP systems may be limited due to decomposition of PFAS precursors to PFOA and other PFCAs as unreactive transformation products (Bruton and Sedlak 2017).

CHP systems that predominantly generate hydroxyl radicals partially transform PFAAs to their PFCAs of related perfluorinated chain length, which are not further transformed (Houtz and Sedlak 2012; Bruton and Sedlak 2017). Systems that generate superoxide and hydroperoxide have been demonstrated at the bench test level to mineralize PFOA (Mitchell et al. 2014), but effectiveness with other PFAS is unknown.

12.6.3.3 Activated Persulfate

Persulfate anion ($S_2O_8^{2-}$) is activated to generate reactive radical species, primarily sulfate radicals (2.6 volts, or V) and hydroxyl radicals (2.7 V). Methods to activate persulfate include transition metals, high pH, and heat activation (Siegrist, Crimi, and Simpkin 2011). Hydroxyl radicals are the predominant radicals formed at high pH conditions (Furman et al. 2011), while at acidic pH there is greater yield of sulfate radicals (Siegrist, Crimi, and Simpkin 2011).

PFCAs are attacked by sulfate radicals under acidic conditions, initiating a decarboxylation reaction, where cleavage of the carbon-to-carbon (C-C) bonds occurs between PFCAs and the carboxyl group (-COOH), forming unstable perfluoroalkyl radicals (C_nF_{2n+1}) (Hori et al. 2010; Lee et al. 2012; Yin et al. 2016). A stepwise series of decarboxylation and hydrogen fluoride (HF) elimination reactions continues to form shorter chain PFCAs until all PFCAs are mineralized to fluoride and carbon dioxide. PFSAs such as PFOS are unreactive with sulfate radicals (Park et al. 2016; Bruton and Sedlak 2017). Hydroxyl radicals attack the alkyl groups of both PFCAs and PFSAs, but do not attack the perfluoroalkyl chain. As a result, PFCA and PFSA precursors are transformed to PFCAs of related perfluorinated chain length (Bruton and Sedlak 2017). Under alkaline pH conditions the sulfate and hydroxyl radicals are reactive with the alkyl groups but similarly unreactive with the perfluoroalkyl chain, which is the basis of the TOP method (Houtz and Sedlak 2012).

Activated persulfate under acidic conditions has proven effective for PFOA (PFCAs) with nominal 100% degradation, but PFOS is not transformed. Sulfate radicals and hydroxyl radicals generated by alkaline persulfate activation transform PFCA and PFSA precursors to PFCAs of related perfluorinated chain length (Bruton and Sedlak 2017).

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER-2423 In Situ Treatment Train for Remediation of Perfluoroalkyl Contaminated Groundwater: In Situ Chemical Oxidation of Sorbed Contaminants (ISCO-SC)
- ER201729 Field Demonstration to Enhance PFAS Degradation and Mass Removal Using Thermally Enhanced Persulfate Oxidation Followed by Pump-and-Treat
- ER18-1545 Innovative Treatment of Investigation-Derived Waste Polluted with Per- and Polyfluoroalkyl Substance Contaminants and Other Co-Contaminants.

12.6.3.4 Sonochemical Oxidation/Ultrasound

The sonochemical process relies on the propagation of acoustic waves in liquids at frequencies ranging between 20 kHz and 1,000 kHz (Furuta et al. 2004), which results in cavitation. Operating parameters such as frequency (Campbell and Hoffmann 2015), power density (Hao et al. 2014), solution temperature, sparge gas, and initial concentration of PFAS (Rodriguez-Freire et al. 2015) play a significant role in the sonochemical degradation and defluorination rate of PFAS (Cao et al. 2020). Sonochemical degradation occurs via two mechanisms: localized thermal treatment and free radical destruction (Rayaroth, Aravind, and Aravindakumar 2016). During cavitation, cyclic formation, growth, and collapse of micro/nano bubbles result in an intense increase in temperature and pressure (5000 Kelvin (K) and 2000 atmosphere (atm)), along with the generation of free radicals (Furuta et al. 2004; Chowdhury and Viraraghavan 2009).

Sonochemical oxidation has been successfully applied for rapid degradation of PFAS to fluoride (F^-), sulfate (SO_4^{2-}) and carbon dioxide (CO_2). Vecitis et al. (2008) reported a complete recovery of SO_4^{2-} and >90% defluorination of PFOA and PFOS with initial concentrations of 0.24 µM and 0.20 µM, respectively, for a field-scale application to treat groundwater from below a landfill. At bench scale, sonolysis has been reported in the literature as one of the most effective treatment processes for PFAS-contaminated water, because they almost immediately mineralize to SO_4^{2-}, CO_2, carbon monoxide (CO), and F^- after cleavage of their C-C/C-S bond. Studies have reported >90 percent degradation and defluorination for PFOA and PFOS (Moriwaki et al. 2005; Vecitis et al. 2008; Cheng et al. 2008, 2010). Gole et al. (2018) demonstrated removal and defluorination of AFFF in a 91-L sonolytic reactor. Lei et al. (2020) showed a synergistic treatment effect of a combined persulfate/ultrasound approach.

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER21-5045 Sonolysis-based In Situ PFAS Treatment within an HRX Well
- ER21-1018 Thermal Destruction of PFAS by Hydrodynamic Cavitation
- ER22-3394 Pulsed Electrosorptive Cavitation: A Cohesive Approach for Complete Mineralization of PFAS in Aqueous Systems
- ER22-3150 Engineering an “All-In-One” Biochar-Surfactant System for Enhanced PFAS Sorption and Reductive Degradation Using a Coupled Ultraviolet and Ultrasonication Approach

12.6.3.5 Photolysis/Photochemical Oxidation

A thorough review of photolysis/photochemical oxidation technology for PFAS decomposition is reported in Wang et al. (2017). Chen, Zhang, and Liu (2007) and Giri et al. (2011) reported removal of PFAS by direct photolysis at 185 nm. Hori et al. (2004) and Chen, Zhang, and Liu (2007) reported that direct photolysis at 254 nm alone is not very effective because PFAS do not absorb light at wavelengths >220 nm due to their chemical structure. Chemical reagents/catalysts such as Fe^{3+}, $S_2O_8^{2-}$, TiO_2, heteropolyacid photocatalyst ($H_3PW_{12}O_{40}$), CO_3^{2-}, and IO_4^- when combined with ultraviolet (UV) (>220 nm) light can effectively decompose PFAS (Hori et al. 2005; Chen and Zhang 2006; Zhang, Pan, and Zhou 2016; Hori et al. 2007; Wang et al. 2008; Cao et al. 2010; Gomez-Ruiz et al. 2018). This is due to generation of strong and reactive oxidative species such as $OH^{\bullet}$, $H^{\bullet}$, $CO_3^{\bullet-}$ and PFAS-Fe complexes. Photochemical oxidation of PFAS is said to be dependent on the light source (UV or vacuum ultraviolet), initial concentration of PFAS, environmental matrix, temperature, pH, and type of reagent used (Lin et al. 2012; Giri et al. 2012; Lyu et al. 2015, 2015; Xu et al. 2017). Use of non-traditional photocatalytic methods such as fixating a photocatalyst within a porous media (McIntyre et al. 2023; McIntyre et al. 2022; McIntyre et al. 2021; McIntyre and Hart 2021) or the use of boron nitride may enhance destructive performance (Qanbarzade et al. 2023).

The major degradation pathways involved in the photochemical oxidation of PFAS are direct photolysis and free radical reactions. The C-C bond between PFAS is cleaved with the COOH group to form perfluoroalkyl radicals (Hori et al. 2003; Hori et al. 2008), which then react with water and undergoes hydrogen fluoride elimination to form shorter chain compounds (Liu et al. 2017). These then undergo hydrolysis to form subsequent shorter PFAS (losing CF2 units). During direct photolysis, the C-C and C-S bonds of PFAS are broken by photoelectrons to generate perfluoroalkyl radicals and carbon dioxide (Wang et al. 2017).

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER18-1595 A Combined Photo/Electrochemical Reductive Pathway towards Enhanced PFAS Degradation
- ER18-1513 Effective Destruction of Per- and Polyfluoroalkyl Substances in Water by Modified SiC-based Photocatalysts
- ER18-1515 A Cost-Effective Technology for Destruction of Per- and Polyfluoroalkyl Substances from DOD Subsurface Investigation-Derived Wastes
- ER18-1599 Pilot-scale Assessment of a Deployable Photocatalytic Treatment System Modified with BiPO4 Catalyst Particles for PFAS Destruction in Investigation-Derived Wastewater
- ER19-1403 Validation of UV/TiO2 Activated Alkaline Media (CFM) for Destruction of PFAS in Concentrated Liquid Waste Streams
- ER22-3258 Chemical-free Light-driven Destruction of Per- and Polyfluoroalkyl Substances Using Non-toxic Boron Nitride (BN)
- ER22-3187 Destruction of PFAS using Plasmonic Photocatalysts

12.6.3.6 Electrochemical Treatment

Electrochemical treatment occurs via anodic oxidation; a variety of materials have been used as anodes. The treatment effectiveness of PFOS and PFOA using different anodes can vary significantly. Most research on PFAS, particularly PFOS and PFOA removal, has been conducted using a boron-doped diamond (BDD) electrode due to its mechanical, chemical, and thermal stability (Trautmann et al. 2015; Schaefer et al. 2017; Schaefer et al. 2019; Wang et al. 2019). Some other electrodes, such as lead dioxide (PbO_2), titanium oxide (TiO_2), titanium suboxide ($Ti4O_7$), and tin oxide (SnO_2), also have the ability to treat PFAS-contaminated water (Ochiai et al. 2011; Zhou et al. 2012; Zhao, Gao, et al. 2013; Liang 2017; Liang et al. 2018). Operating conditions and parameters such as pH (Lin et al. 2012; Zhou et al. 2012), current density, electrolyte type (Song et al. 2010; Zhuo et al. 2012), electrode distance (Lin et al. 2012), initial PFAS concentration, and temperature are important factors that influence electrochemical oxidation of PFAS (Niu et al. 2016).

Electrochemical treatment proceeds via direct and indirect anodic oxidation (Radjenovic and Sedlak 2015; Niu et al. 2016; Schaefer et al. 2018). In direct electrolysis, contaminants are adsorbed onto and degraded directly at the electrode, while in indirect electrolysis, contaminants are degraded in the bulk liquid in reactions with oxidizing agents (that is, hydroxyl radicals) formed at the electrode (Radjenovic and Sedlak 2015).

Bench-scale studies have shown success in the degradation and defluorination of PFAS, including short-chain, long-chain PFAAs as well as PFAA precursors (Chiang 2018). Electrochemical oxidation of precursors may lead to the transient generation of perfluorinated carboxylates (Schaefer et al. 2018). Ultimately, fluoride is released, with typical recoveries ranging from 60 to 80%; the fate of the remaining fluoride is unknown, but studies have suggested that losses due to volatile perfluorinated alkanes may occur.

Electrochemical treatment has been tested as a stand-alone technology for PFAS concentrations at ppb levels and as a destruction technology to destroy concentrated PFAS waste streams generated from other treatment technologies such as ion exchange and foam fractionation (Liang et al. 2018; Chiang 2018). It has been partially demonstrated as an ex situ treatment of PFAS. But in situ application is also being considered and funded in the SERDP program. The issue of perchlorate formation as a byproduct during electrochemical oxidation of PFAS has been addressed by Schaefer et al. (2017) using a biological treatment polishing step. The issue can also be minimized by not using sodium chloride as the electrolyte (Chiang 2018).

The technology has been demonstrated via bench studies and pilot-scale reactor to be very effective for treatment of short-chain, long-chain PFAAs, as well as most commonly detected PFAA precursors in spike water systems and several remediation-derived waste streams laden with high PFAS concentrations.

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER-2424 Investigating Electrocatalytic and Catalytic Approaches for In Situ Treatment of Perfluoroalkyl Contaminants in Groundwater
- ER-2718 Synergistic Treatment of Mixed 1,4-Dioxane and PFAS Contamination by Combining Electrolytic Degradation and Electrobiostimulation
- ER18-1320 Electrochemical Oxidation of Perfluoroalkyl Acids in Still Bottoms from Regeneration of Ion Exchange Resins
- ER-2717 A Novel Reactive Electrochemical Membrane System for Treatment of Mixed Contaminants
- ER18-1491 Reactive Electrochemical Membrane (REM) Reactors for the Oxidation of Perfluoroalkyl Compound Contaminated Water
- ER22-3184 Deep Destruction of PFAS in Complicated Water Matrices by Integrated Electrochemical Oxidation and UV-Sulfite Reduction
- ER22-3394 Pulsed Electrosorptive Cavitation: A Cohesive Approach for Complete Mineralization of PFAS in Aqueous Systems

12.6.3.7 Solvated Electrons (Advanced Reduction Processes)

Advanced reduction processes (ARP) has been investigated for the reductive degradation of groundwater contaminants. ARP involves the combination of activation methods such as ultrasound, ultraviolet, microwaves, and electron beam with reducing agents (reductants) such as ferrous iron, sulfide, sulfite, iodide, and dithionite to generate very reactive reducing radicals and the hydrated electrons (e−aq) that mineralize contaminants to less toxic products (Vellanki, Batchelor, and Abdel-Wahab 2013). The reducing hydrogen radical ($H^{\cdot}$) and the hydrated electron are strong reductants that react easily with halogenated organic compounds (Buxton et al. 1988). ARP-induced degradation rates depend on initial solution pH and reductant concentration (Vellanki, Batchelor, and Abdel-Wahab 2013). Bentel et al. (2019) described insights gained from a structure-activity relationship analysis of the mechanisms involved in the reaction of solvated electrons with PFAS. Cui et al. (2020) offered a detailed critical review focused on mechanisms of reductive PFAS destruction by solvated electrons.

The degradation pathway of PFAS using ARP differs from that of oxidizing agents in that the hydrated electron (Song et al. 2013) cleaves the C-F bond adjacent to the functional group of the PFAS rather than the C-C or C-S bond. Qu et al. (2014)

proposed that hydrated electrons lead to the reductive cleavage of the C-F bonds, resulting in fluorine elimination from PFOA. Furthermore, they proposed that under UV irradiation, cleavage of the C-C bond between the COOH group and the perfluoroalkyl group occurred as shorter chain intermediates were detected in solution. Qu et al. (2014) therefore concluded that two reactions are responsible for the reductive defluorination of PFOA: (1) direct photolysis by UV irradiation, and (2) photoreduction by hydrated electrons. Tenorio et al. (2020) showed that PFAS treatment by solvated electrons varies widely among compounds.

Reductive processes have proven feasible for degradation of most PFAS, especially PFOS. It should be recognized that electrons will be scavenged by oxygen, nitrate, and chlorides, and this should be considered for treatment application. Recent research using UV-activated sulfite demonstrated effective generation of hydrated (aka solvated) electrons. Laboratory tests showed >50% defluorination of both PFOS and PFOA within 24 hours (Strathmann 2018).

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER-2426 Quantification of In Situ Chemical Reductive Defluorination (ISCRD) of Perfluoroalkyl Acids in Ground Water Impacted by AFFFs
- ER21-5152 Demonstration of Cost-effective and Sustainable Destruction of PFAS in Concentrated Waste Streams (Hydrated Electrons)
- ER22-3286 Treatment of PFAS-impacted Matrices by Dissolving Metal Reduction with Mechanochemical Mixing
- ER22-3298 Utilizing PFAS Aggregation at the Gas-Water Interface for Energy-Efficient PFAS Destruction
- ER22-3158 Electrocatalytic Reduction of PFAS in Groundwater and Aqueous Concentrates
- ER22-3345 A Novel Redox Material (FeSO3) for Efficient and Rapid Treatment of Concentrated PFAS Matrices
- ER21-7569 Photoactivated Reductive Defluorination PFAS Destruction

12.6.3.8 Plasma Technology

Plasma technology is a promising destructive PFAS treatment technology. Plasma is formed as a result of an electrical discharge from the addition of sufficient energy to gas (Jiang et al. 2014) and is classified into two major groups based on temperature and electronic density: thermal plasma (local thermal equilibrium) and nonthermal plasma (nonequilibrium plasma) (Bogaerts 2002). Due to lower energy requirements and selectivity, nonthermal plasma is most often used in water treatment processes (Jiang et al. 2014). In water treatment plasma applications, electrical discharges can be discharged above the liquid surface, directly to the liquid, or in the form of bubbles in liquids (Locke, Lukes, and Brisset 2012) (Stratton et al. 2017). These electrical discharges diffuse in liquids to initiate various chemical and physical effects, including high electric fields, intense UV radiation, shock waves, and formation of strong oxidative and reductive reactive species ($H^{\bullet}$, $O^{\bullet}$, $OH^{\bullet}$, H_2O_2 aqueous electrons, H_2, O_2, O_3), which are effective for the treatment and removal of contaminants (Lukes, Appleton, and Locke 2004; Lukes et al. 2005; Stratton et al. 2017; Singh et al. 2019).

Determination of plasma treatment mechanisms and degradation pathways for PFAS is a research focus, and several mechanisms and pathways have been proposed. Takeuchi et al. (2013) proposed that the main reaction pathway for PFOA by plasma treatment is by thermal cleavage of the C-C bonds resulting in direct decomposition to gaseous products without formation of shorter chain PFCAs. Others have proposed that PFAS decomposition is due to conversion to unstable radicals during interaction of PFAS with the most energized ions in the plasma (Hayashi et al. 2015; Obo, Takeuchi, and Yasuoka 2015), or with positive ion(s) generated by the plasma (Yasuoka, Sasaki, and Hayashi 2011) at the bubble gas-liquid interface. The unstable radicals produced during PFAS decomposition can result in a sequential loss of one carbon within the chain.

Plasma effectively degrades PFAS in a relatively short period of time (30-minute treatment) in both synthetic water and groundwater. It has been reported that plasma treatment provided 90% degradation of PFOA and PFOS, with only about 10% of the destroyed PFOA and PFOS being converted to shorter chain PFAAs (Stratton et al. 2017). The degradation rate is not affected by the presence of co-contaminants. This is an environment-friendly technology, because there is no demand on pressure or temperature and it does not require significant input of chemicals. Plasma also generates a broad range of reactive species.

Related Past, Ongoing, and Recent Research Funded by SERDP or ESTCP:

- ER18-1306 Combined In Situ/Ex Situ Treatment Train for Remediation of Per- and Polyfluoroalkyl Substance (PFAS) Contaminated Groundwater

- ER18-1624 Plasma Based Treatment Processes for PFAS Investigation-Derived Waste
- ER18-1570 Application of Non-Thermal Plasma Technology for the Removal of Poly- and Perfluorinated Substances from Investigation-Derived Wastes
- ER18-5015 Removal and Destruction of PFAS and Co-contaminants from Groundwater
- ER18-1624 Plasma Based Treatment Processes for PFAS Investigation Derived Waste
- ER22-3316 Complete Destruction of Undiluted AFFF by a Plasma Spinning Disc Reactor
- ER22-3187 Destruction of PFAS Using Plasmonic Photocatalysts
- ER20-5355 An Innovative Plasma Technology for Treatment of AFFF Rinsate from Firefighting Delivery Systems
- ER21-3564 Non-thermal Treatment of Unused AFFF Concentrate by Liquid-phase Plasma Discharge Process

12.6.3.9 Zero-Valent Iron (ZVI)/Doped-ZVI

ZVI is an inexpensive groundwater remediation technology. It is the most commonly used reductant for in situ groundwater remediation. It is a strong reducing agent capable of successfully reducing major groundwater contaminants such as chlorinated solvents. Recently nanoscale zero-valent iron (nZVI) has had increased attention due to its higher reactivity, surface area, and potential in situ injectability compared to the micro-sized ZVI.

In general, the removal of PFAS by ZVI in reductive processes involves the mass transfer of contaminants to the ZVI surface, and their adsorption and reaction (transformation of contaminants into less toxic/nontoxic species) on the ZVI surface, followed by the desorption and mass transfer of byproducts into solution (Arvaniti et al. 2015). Because the reduction of contaminants by ZVI is a surface-mediated electron transfer process, the surface properties of ZVI influence contaminant reactivity. (Arvaniti et al. 2015) found that PFOS removal using Mg-aminoclay-coated nZVI occurred via adsorption of PFOS to the ZVI surface followed by reduction. A similar decomposition mechanism for PFOS using ZVI in subcritical water was reported by Hori et al. (2006), who suggested that adsorption of PFOS onto ZVI played a major role in PFOS decomposition, as fluoride was detected in the treatment solution after treatment.

This technology is highly effective for the removal of PFOS, reacts relatively quickly, and has proven feasible for degradation of most PFAS.

Related Past, Ongoing, and Recent Research Funded by SERDP or Air Force AFWERX:

- ER-2426 Quantification of In Situ Chemical Reductive Defluorination (ISCRD) of Perfluoroalkyl Acids in Groundwater Impacted by AFFFs
- Contract Number FA864921P0368: Reactive Bimetallic-Carbon Media for Destruction of PFAS-Containing Aqueous Fire Fighting Foam Stockpile
- ER22-3286 Treatment of PFAS-impacted Matrices by Dissolving Metal Reduction with Mechanochemical Mixing
- ER22-3345 A Novel Redox Material (FeSO3) for Efficient and Rapid Treatment of Concentrated PFAS Matrices

12.6.3.10 Alkaline Metal Reduction

Alkaline metal reduction involves the use of alkali metals (that is, the reductant) to reduce organic compounds to their anion radical. Reductive degradation of branched PFOS has been reported with vitamin B_{12} as a catalyst and Ti(III)-citrate or nanosized zero-valent zinc as a bulk reductant (Ochoa-Herrera et al. 2008; Park, de Perre, and Lee 2017) where degradation rates increase with increasing solution pH, bulk reductant dose, and temperature.

The degradation pathway of PFAS by alkali metal reduction as postulated by Ochoa-Herrera et al. (2008) suggests that destruction of branched PFOS isomers occurs via chemical reductive dehalogenation. Park, de Perre, and Lee (2017) suggested that the ability of vitamin B_{12} to reduce branched PFOS isomer and not linear is because the branched PFOS isomers possess greater electron density differences that are absent in linear PFOS isomers. Bench-scale studies have shown success for branched PFOS isomers and have proven to be efficient (greater than 70% removal; see Ochoa-Herrera et al. (2008)). In situ applications have not been tested. Removal and defluorination are lower for PFHxS relative to PFOS. Polyfluorinated sulfonate intermediates (C_5-C_8) are the final products (Park, de Perre, and Lee 2017).

Bimetallic $nNiFe_0$ particles supported on activated carbon have demonstrated transformation of both linear- and branched-PFOS isomers, achieving 94% PFOS transformation at 50°C (Zenobio et al. 2020). Transformation byproducts detected in the particle extracts indicate defluorination and desulfonation pathways.

12.6.3.11 High-Energy Electron Beam (eBeam)

High-energy electron beam (eBeam) is a high efficiency, flow-through, nonthermal, chemical-free technology that utilizes electron accelerators to generate large numbers of highly energetic electrons from electricity (Cleland 2011; Pillai and Shayanfar 2016). The technology has been commercialized globally for pasteurizing foods, sterilizing medical devices, cross-linking polymers, and eliminating insects and pests from fresh produce (Cleland 2011; Pillai 2016; Pillai and Shayanfar 2016; Zembouai et al. 2016). It provides a form of ionizing irradiation that does not involve the use of radioactive isotopes. The amount of energy from eBeam that is absorbed by an irradiated material per unit mass is called dose. The absorbed dose during eBeam treatment depends on the type and thickness of the material, the beam power, and the length of time the material is exposed to the electron beam (Waite 1998).

eBeam is applicable for use on soil and liquid matrices for many purposes: disinfection of sewage sludge (Praveen et al. 2013; Waite 1998); remediation of heavy hydrocarbon-contaminated soils (Briggs 2015); and remediation of volatile organic compounds (VOCs) and semivolatile organic compounds in liquid wastes such as groundwater, wastewater, and landfill leachate (USEPA 1997). During irradiation of water, three primary reactive species are formed: solvated electrons and hydrogen radicals, which are strong reducing species, and hydroxyl radicals, which are strong oxidizing species. This creates both advanced reduction and oxidation processes without the addition of any chemicals. The absolute concentration of radicals formed during irradiation is dose- and water quality-dependent, but it has been measured at greater than millimolar (mM) levels in potable, raw, and secondary wastewater effluent (Waite 1998).

Researchers at Texas A&M University recently demonstrated defluorination of PFOA in aqueous samples by eBeam technology (Wang et al. 2016). The study measured defluorination efficiency as a function of molar concentration of free fluoride ions and initial molar concentration of PFOA to be treated. Final defluorination efficiencies ranged from 34.6 to 95% under various increasing concentrations of nitrate, alkalinity, and fluvic acid. The defluorination is possibly due to the formation of aqueous electrons and the formation of secondary radicals (Wang et al. 2016). Kim et al. (2019) demonstrated eBeam defluorination of PFOS when used in combination with chemical oxidants.

An additional study further demonstrated eBeam-mediated defluorination of PFOS and PFOA with decomposition efficiencies of 95.7% for PFOA and 85.9% for PFOS in an anoxic alkaline solution (pH = 13). Radical scavenging experiments indicated that the aqueous electron and hydrogen radical were important in the eBeam degradation of PFOA and PFOS (Ma et al. 2017). Further evaluation of this technology for treating other PFAS (polyfluorinated precursors and other long- and short-chain PFAAs) in soil and water, as well as testing over a range of concentrations, will be necessary to further understand treatment performance potential and to identify any deleterious byproducts.

Related Ongoing Research Sponsored by SERDP:

- ER18-1620 Ex Situ Remediation of Investigation-Derived Wastes containing PFAS by Electron Beam Technology

12.6.3.12 Supercritical Water Oxidation

Supercritical water oxidation (SCWO) is a destructive technology that uses unique properties of water above its critical point at 374°C and 3200 psi, which is where distinct liquid and gas phases do not exist, but is below the pressure required to compress it into a solid. Thus, SCWO is a high temperature and pressure technology that offers important environmental advantages for treating industrial wastes and sludges. SCWO, also known as hydrothermal oxidation, has homogeneous reaction conditions between oxidizing materials and added oxygen or hydrogen peroxide as the oxidizing agent, which creates an aggressive oxidative environment. The reaction of SCWO can also be heterogeneous when the organic material is a solid, in the case of heterogeneous catalytic SCWO.

SCWO is not a new technology and has been evaluated and applied to various organic compounds in liquid streams for decades (Tester et al. 1993). With the appropriate reaction temperatures, pressures, and residence times, almost any organic pollutant can be destroyed by SCWO. More recently, with a focus on PFAS, bench- and pilot-scale systems have been evaluated (Jama et al. 2020; Hori et al. 2008; USEPA 2021; McDonough et al. 2022; Krause et al. 2022; Li et al. 2023).

Although different oxidant sources (air, oxygen, hydrogen peroxide) can be used for SCWO reactions, destruction of PFAS is independent of the oxygen source used for SCWO process. Higher temperatures have shown effective destruction of all PFAS. Reactor temperatures ≥450°C destroyed perfluorinated carboxylic acids; however, temperatures of ≥575°C are shown to destroy perfluorosulfonic acids (Scheitlin et al. 2023). Because the types of aqueous waste matrices are quite complex and widely different, process optimization is needed. Researchers are performing feasibility testing to increase the throughput and effectiveness of the large-scale treatment of aqueous waste matrices (Rosansky 2021; Krause et al. 2022;

Scheitlin et al. 2023). These complex waste streams do not affect the destruction efficacy of perfluorinated carboxylates, perfluorinated sulfonates, or their precursors and intermediates (Krause et al. 2022; Scheitlin et al. 2023).

SCWO can also effectively destroy co-contaminants such as petroleum hydrocarbons and volatile organic compounds, which are commonly found at many of the AFFF-impacted fire training areas. SCWO has been documented to treat aqueous matrices impacted by multiple organic contaminants (Rosansky 2021; Scheitlin et al. 2023; ER22-7338).

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER20-5350 Supercritical Water Oxidation (SCWO) for Complete PFAS Destruction
- ER22-3384 Bench-Scale Demonstration of PFAS Destruction in Solid Using Supercritical Water Oxidation
- ER22-7338 Bench-Scale Evaluation of Supercritical Water Oxidation (SCWO) to Destroy PFAS in Aqueous Investigation-Derived Waste and Complex Waste Streams

12.6.4 Biodegradation

A limited number of studies have tested microbial degradation of PFAS and many conflicting reports exist, all suggesting that more work needs to be performed to fully understand the biotic transformations of these compounds.

Microbial degradation of PFAS has been observed to occur with polyfluoroalkyl substances (Butt, Muir, and Mabury 2014), which contain some carbon-hydrogen bonds instead of C-F bonds (Buck et al. 2011). Recent research documented the aerobic biotransformation of fluorotelomer thioether amido sulfonate (FtTAoS) over a 40-day period to produce 4:2, 6:2, and 8:2 fluorotelomer sulfonate (FTS), 6:2 fluorotelomer unsaturated carboxylic acid (FTUCA), 5:3 fluorotelomer carboxylic acid (FTCA), and C4 to C8 perfluorinated carboxylic acids (Harding-Marjanovic et al. 2015). An unintended consequence of biologically mediated transformations is the conversion of precursors (polyfluorinated) to perfluorinated compounds.

PFOA and PFOS have been shown to be resistant to microbial biotransformation under a variety of growth conditions (Liu and Mejia Avendaño 2013). However, other PFAS, including chemicals in AFFF with nonfluorinated alkyl groups (polyfluorinated substances), are likely amenable to biotransformation. Most recently, defluorination of PFOA and PFOS were observed using an ammonium oxidizing autotroph (Huang and Jaffé 2019). Upon addition of PFOA or PFOS (0.1 mg/L and 100 mg/L, respectively) to the A6 culture, shorter chain perfluorinated products and acetate were observed. Incubations with hydrogen as a sole electron donor also resulted in the defluorination of up to 60% of PFOA and PFOS during 100-day incubations, while total fluorine (organic plus fluoride) remained constant. Reductive defluorination of perfluoroalkyl substances may be possible, as observed when using vitamin B12 and Ti(III)-citrate (Ochoa-Herrera et al. 2008).

Research on the fungal degradation of PFAS has been ongoing due to the wide spectrum of substrate reduction catalyzed by extracellular ligninolytic enzymes. Experiments with white-rot fungus showed limited degradation of PFOA in microcosm studies under certain conditions (Tseng 2012). The innovative delivery of fungal enzymes for PFAS treatment requires further research.

The biodegradation of PFAS has been reported in a few studies as described above and in the following: 8:2 FTOH (Wang et al. 2009), 6:2 FTOH (Liu et al. 2010), 6:2 FTS (Wang et al. 2011), and N-ethyl perfluorooctane sulfonamidoethanol (Rhoads et al. 2008; Rhoads et al. 2013). Recently the PFOA-degrading strain YAB1 was isolated from soil that had been impacted by perfluorinated compounds through acclimation and enrichment culture, where perfluorooctanoic acid (PFOA) was amended as the sole carbon source (Yi et al. 2016). “This strain was preliminarily identified as Pseudomonas parafulva based on colony morphology, physiological and biochemical features, and 16S rRNA gene sequencing. Using shaking flask fermentation, the maximum tolerable concentration of YAB1 on PFOA was found to be 1,000 mg/L” (Yi et al. 2016), and the optimal PFOA concentration for the growth of YAB1 was 500 mg/L. After 96 hours of culture, the PFOA degradation rate was “32.4%. When 1 g/L glucose was added to the inorganic salt culture medium, the degradation rate increased to 48.1%. Glucose was the best exogenous carbon source for the degradation of PFOA” (Yi et al. 2016).

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER-2422 Bioaugmentation with Vaults: Novel In Situ Remediation Strategy for Transformation of Perfluoroalkyl Compounds
- ER-2127 Remediation of Perfluoroalkyl Contaminated Aquifers using an In Situ Two-Layer Barrier: Laboratory Batch and Column Study
- ER20-1023 Microbially-Mediated Defluorination of High-Priority Per- and Polyfluoroalkyl Substances:

Microorganisms, Genetics, and Biochemistry

- ER20-1219 Biotransformation and Potential Mineralization of PFOS, PFHxS, and PFOA by Acidimicrobiaceae sp. A6 under Iron Reducing Conditions
- ER20-1430 Biodegradation of Per- and Polyfluoroalkyl Substances (PFASs) via Superoxide-Hyper-Producing Bacteria
- ER20-1541 Identification, Characterization, and Application of Reductive Defluorinating Microorganisms
- ER22-3312Cometabolic Transformation and Treatment of PFAS Precursors in PFAS-Impacted Soils and Aquifer Sediments

12.6.5 Alkaline Hydrothermal Reaction

Alkaline hydrothermal treatment involves degradation of PFAS under high pressure, high temperature, and high pH conditions. Wu et al. (2019) demonstrate rapid destruction of particularly recalcitrant PFOS during hydrothermal treatment of a solution amended with NaOH. They propose an initial cleavage of the functional group catalyzed by OH-, followed by sequential chain-shortening and decarboxylation to produce carbonate and fluoride salts. Other researchers (Li et al. 2022; Hao et al. 2021, 2022) have demonstrated PFAS degradation in a variety of matrices, but generally long residence times (> 30 minutes) have been required for high degrees of PFAS degradation (for example, > 90%). Pinkard et al. (2023) demonstrated greater than 99% degradation in a continuous flow system.

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER18-1501 Hydrothermal Technologies for On-Site Destruction of Site Investigation Wastes Impacted by Per- and Polyfluoroalkyl Substances (PFAS)
- ER22-3157 Hydrothermal Destruction of Per- and Polyfluoroalkyl Substances during Designer Biochar Reactivation

12.6.6 Deep Well Injection

A potential alternative to treatment may be the use of on-site or off-site underground injection waste disposal wells for liquids containing PFAS. The USEPA (2020) considered deep well injection as one of three viable, commercially available disposal options. This approach eliminates discharges to surface water and groundwater, which could be a consideration given the present climate of varying discharge limitations for PFAS. However, deep well injection is not a destruction technology.

Class I wells, as defined by USEPA, are acceptable for both hazardous and nonhazardous liquid wastes (USEPA 2019). The USEPA has published guidance on the requirements for the use of injection wells, which include siting, construction, operation, monitoring, testing, record keeping, reporting, and closure (USEPA 2019). The USEPA has also studied the risks associated with underground injection wells (USEPA 2001), and these risks should be considered for the use of underground injection wells for PFAS-laden water. This option may be most attractive as a disposal option for high concentration liquids, such as RO reject water, anion exchange regeneration fluids, wastewater from manufacturing sites, and landfill leachate.

12.6.7 Monitored Natural Attenuation

Definition of MNA “The term “monitored natural attenuation,” refers to the reliance on natural attenuation processes (within the context of a carefully controlled and monitored site cleanup approach) to achieve site-specific remediation objectives within a time frame that is reasonable compared to that offered by other more active methods” (USEPA 1999).

12.6.7.1 Introduction

Monitored natural attenuation (MNA) is fundamentally a risk management strategy. MNA is not a “presumptive” or “default” remedy—it represents a remedy component option that should be evaluated alongside other applicable remedy component options, including in combination with active treatment (for example, active treatment of “hot spots” and MNA for distal segments of a plume or as part of a treatment train). MNA is not considered a “no action” or “walk-away” approach but is rather considered “an alternative means of achieving remediation objectives that may be appropriate for specific, well-documented site circumstances where [the implementation of MNA] meets the applicable statutory and regulatory requirements” (USEPA 1999). In its guidance for the cleanup of contaminated soil and groundwater in the Superfund, RCRA Corrective Action, and Underground Storage Tank Programs, USEPA noted that “…there is often a variety of methods available for achieving remediation objectives at any given site, MNA may be evaluated and compared to other viable remediation methods (including innovative technologies) during the study phases” (USEPA 1999) informing remedy selection and periodically thereafter. A comprehensive long-term monitoring program is critical to any MNA remedy component to verify its continued viability. If plume migration trend data suggest a potential threat to receptors or lack of progress toward remediation objectives, additional contingency measures are likely to be to be required.

Attenuation Processes The "natural attenuation processes" include a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater. These in situ processes include biodegradation; dispersion; dilution; sorption; volatilization; radioactive decay; and chemical or biological stabilization, transformation, or destruction of contaminants." (USEPA 1999).

MNA has been proposed as a strategic component to manage PFAS impacts at some sites (Newell et al. 2021, 2021). MNA is an established management approach for a variety of contaminant classes that are subject to natural attenuation processes when released to the environment, including petroleum hydrocarbons and chlorinated solvents (USEPA 1999). In addition, MNA is an established management approach for certain metals and other inorganic constituents that do not degrade but are attenuated through various nondestructive processes (ITRC 2010; USEPA 2015), which can be considered analogous to PFAS. Although there are currently no recognized destructive attenuation mechanisms for PFAAs, numerous biotic and abiotic transformation pathways have been documented for several polyfluorinated PFAS (see Section 5.4). As research regarding natural attenuation mechanisms for PFAS continues, it is possible that additional biotic and abiotic attenuation pathways (including transformation, destruction, or mineralization) may be identified.

The predominant known processes for PFAS natural attenuation are those that contribute to plume stability resulting from natural retardation of PFAS transport and promote retention of PFAS mass in the subsurface away from potential receptors. These include solid phase partitioning (Section 5.2.3), partitioning at the air-water interface (Section 5.2.4.1), natural advection mechanisms, and matrix diffusion (Section 5.3.1).

In the subsurface, physical and geochemical processes can result in a stable plume by slowing PFAS migration through the unsaturated zone, reducing or preventing the mass discharge from the unsaturated zone to an underlying aquifer, and slowing the rate of PFAS migration within the saturated zone. The preferential sorption characteristics of polyfluorinated compounds with cationic or zwitterionic head groups can also promote attenuation (refer to Section 10.4.6). This represents a form of "chemical retention" (Newell et al. 2021) because if naturally retained in the untransformed, cationic, or zwitterionic precursor state these compounds are anticipated to move more slowly than if they were transformed to more mobile anionic PFAAs.

12.6.7.2 Considerations for an MNA Remedy Component

MNA may be most applicable to PFAS sites with some combination of a stable plume, a long travel time to the nearest receptor, and low and/or decreasing mass discharge rates. A stable plume may be demonstrated if the attenuation rate offsets the migration rate (that is, steady state condition) (see Section 10.4.7). Practitioners may rely on multiple strategies, including concentration trend analysis, to demonstrate the degree to which PFAS plumes may be attenuating and/or stabilizing.

For documented stable plumes, and in the absence of immediate risk receptors or where exposures can be controlled, MNA may be considered as an effective management approach for the following scenarios: 1) as a final remedy component for plume segments where a comprehensive data set demonstrates natural attenuation trends that can achieve comparable reduction rates and time frames to attain the remediation objectives for PFAS groundwater concentrations versus active treatment technologies (for example, lower parts per trillion plumes or distal plume segments; scatter/random PFAS detections that do not represent a defined plume); or 2) as a final treatment train step to reach low parts per trillion cleanup levels once active treatment has reached a defined interim treatment objective or plateau condition/point of diminishing returns (assuming lines of evidence supporting MNA has been established).

Given the evolving state of understanding and associated uncertainties regarding the behavior of PFAS in the environment, development of reliable PFAS fate and transport models that are rigorous and include the derivation of site-specific parameters that govern PFAS fate and transport will be needed. High-resolution site characterization methods (including tracer studies) and fate and transport modeling may be beneficial in evaluating natural attenuation of PFAS. Consideration of MNA as a potential element of a remedial strategy may require implementation of source control measures (that is, hydraulic modifications, in situ injections, removals, etc.) and/or demonstration of stable conditions.

Comprehensive PFAS fate and transport modeling is further complicated by the uncertainties of precursor PFAS transformation in the environment. For more information regarding PFAS fate and transport modeling and assessing plume stability, see Assessing Plume Stability in Section 10.4.8.

Until a more thorough understanding of PFAS attenuation is developed, consideration of MNA should be evaluated cautiously, whether as the primary or complimentary technology at PFAS contaminated sites.

Related Past, Ongoing, and Recent Research Funded by ESTCP:

- ER21-5198 Developing a Framework for Monitored Natural Attenuation at PFAS Sites

12.7 Limited Application and Developing Solids Treatment Technologies

The treatment technologies presented in this document are provided in a hierarchy defined in Section 12.1, based on level of implementation and level of confidence in the technology from peer-reviewed literature and extent of documented performance. The three development levels include field-implemented technologies, limited application technologies, and developing technologies. Where appropriate in the text both in situ and ex situ technologies are discussed. However, it is not always clear if a limited application or developing technology may be effective in situ, ex situ, or both, thus further distinction between in situ and ex situ is not made in this section. Table 12-1 Treatment Methods Table Excel File presents limited application and developing technologies for solids, which may be applicable to soil, sediments, biosolids, or other solid media, including PFAS-laden materials (for example, GAC, resin, scrubbers, filters). Thermal treatment warrants further discussion as a limited application technology because it has been field-demonstrated at multiple sites by multiple practitioners but has not been well documented in peer-reviewed literature.

12.7.1 Sorption and Stabilization/Solidification

Limited application and developing materials being demonstrated or developed for sorption and stabilization include minerals (for example, organically modified clays) or stabilization agents (for example, Portland cement). Stabilization/solidification through mixing with cementitious materials (for example, Portland cement or other amendments) can be applied to encapsulate PFAS-impacted soil/sediment to restrict PFAS leaching or migration. In situ solidification is always performed with soils in place, and it is necessary to use specialized equipment and maintain careful control over the addition of amendments and water content. In batch experiments, a reduction of 95-99% of leachable anionic PFAS, including PFOS and PFOA, was achieved with amending contaminated soil with 0.5% to 5% by weight of a commercially-available surface-modified clay (Wang et al. 2021). Other laboratory (Willett and Geary 2021) and in situ field studies (McDonough et al. 2021) on soils mixed with up to 10% by weight of this surface-modified clay showed reduction in leaching of a number of PFAS. In situ solidification is intended to yield a high-compressive-strength monolith that has low permeability. A bench-scale study (Sörengård, Kleja, and Ahrens 2019) indicated that solidification using a binder (combination of Portland cement, fly ash, and ground granulated blast-furnace base slag) at a ratio of 9:1 reduced leaching for 13 out of 14 PFAS (except for PFBS). Introducing additional additives (for example, activated carbon, surface-modified clays) at a 2% concentration can further reduce leaching of PFAS in solidification-treated soil.

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER22-3124 A New Concept of “Release-Capture-Destruction” to Enable Remediation of PFAS in Source Zone Soils
- ER18-1652 Destruction of PFAS and Organic Co-Occurring Chemicals

12.7.2 Thermal Treatment

Thermal treatment is defined as mobilization or destruction, or both, of chemicals using heat. This can be accomplished by thermal desorption or thermal destruction. Heat is applied directly or indirectly to the PFAS-contaminated soil/sediment.

Ex situ thermal treatment has been demonstrated (450–954°C) at field pilot-scale studies by a few technology vendors and is considered a partially demonstrated technology (Endpoint Consulting 2016; Enviropacific 2017; Colgan et al. 2018; Grieco and Edwards 2019). The effectiveness depends upon the ability to deliver heat to achieve sufficient and evenly distributed temperature at field scale cost-effectively. The pilot studies conducted have reported >90% removal of PFAS from soil when high heat has been applied.

In addition, lower temperature thermal desorption has been demonstrated to be effective for PFAS at 350–400°C on the bench scale. During a recent proof of concept laboratory bench test, 99.99% removal of PFAS from soils was demonstrated while heating the target volume to 400°C (Crownover et al. 2019; DiGuiseppi, Richter, and Riggle 2019).

No documented examples of in situ thermal treatment for PFAS-impacted soil have been identified. However, the ex situ testing at 350–400°C suggests that these temperatures are sufficient for desorption of PFAS and therefore in situ treatment is potentially feasible for PFAS.

At bench, pilot, and field scales, limited data sets are available and data gaps still exist mainly regarding fate of volatilized PFAS and air emissions (Lassen et al. 2013; USEPA 2020). Another concern is the volatilization of hydrogen fluoride, which could pose serious health and safety issues and could compromise equipment components. Hydrofluoric acid and other non-PFAS off-gas concerns can be managed through conventional off-gas treatment systems (scrubbers), as is further described in Section 12.5 (Air Treatment). Although air emissions from the thermal treatment of PFAS have not been thoroughly studied at the field scale to date, some limited field-implemented air emission studies from the thermal treatment of PFAS have been completed (Barr Engineering 2022; Chemours 2022). PFAS treatment via high temperature air incineration and subsequent acid-gas scrubbing is a common practice during carbon reactivation (Mimna 2017).

Pyrolysis and gasification are often described as heat-induced thermal decomposition processes, though these processes are not solely focused on treatment and are typically used to convert a waste product into a useful feedstock for another product, such as energy, fuels, and chemical commodities. These technologies have only recently been evaluated with respect to treating PFAS (Winchell et al. 2022; Thoma et al. 2022; Bamdad et al. 2022; DiStefano et al. 2022).

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER18-1501 Hydrothermal Technologies for On-Site Destruction of Site Investigation Wastes Contaminated with Per- and Polyfluoroalkyl Substances (PFASs)
- ER18-1556 Small-Scale Thermal Treatment of Investigation-Derived Wastes (IDW) Containing Per- and Polyfluoroalkyl Substances (PFAS)
- ER18-1572 Evaluation of Indirect Thermal Desorption Coupled with Thermal Oxidation (ITD/TO) Technology to Treat Solid PFAS-Impacted Investigation-Derived Waste (IDW)
- ER18-1593 Demonstration of Smoldering Combustion Treatment of PFAS-Impacted Investigation-Derived Waste
- ER18-1603 Field Demonstration of Infrared Thermal Treatment of PFAS-Contaminated Soils from Subsurface Investigations
- ER18-1672 Evaluation of Indirect Thermal Desorption Coupled with Thermal Oxidation (ITD/TO) Technology to Treat Solid PFAS-Impacted Investigation-derived Waste
- ER19-1408 Analysis of Fate of PFAS During Incineration
- ER20-5250 In Situ Thermal Treatment of PFAS in the Vadose Zone
- ER20-5198 Ex Situ Thermal Treatment of Perfluoroalkyl and Polyfluoroalkyl Substances
- ER20-5350 Supercritical Water Oxidation (SCWO) for Complete PFAS DestructionER21-1288 Multi-Scale Evaluation of PFAS Thermal Destruction Requirements
- ER21-1107 Improved Understanding of Thermal Destruction Technologies for Materials Laden with Per- and Polyfluoroalkyl Substances
- ER21-1019 A Quantum Chemical – Machine Learning Approach for the Prediction of Thermal PFAS Destruction
- ER21-1234 Experimental and Theoretical Validation of the Chemical Kinetics for the Thermal Destruction of Perfluoroalkyl Alkyl Substances
- ER21-1135 Improving Low Temperature Thermal Treatment of Per- and Polyfluoroalkyl Substances (PFAS) and Infrared (IR) Spectroscopy Methods to Monitor Treatment Efficacy
- ER20-5250 In Situ Thermal Treatment of PFAS in the Vadose Zone
- ER20-5198 Ex Situ Thermal Treatment of Perfluoroalkyl and Polyfluoroalkyl Substances
- ER21-1256 Develop Synergetic Novel Macrocycle-based Sorbents with Thermal Destruction for Enhanced PFAS Removal in Groundwater and Drinking Water Treatment
- ER21-1117 Thermal-Enhanced Photochemical and Alkaline Destruction of PFAS in Sorbent Regenerants and Membrane Concentrates
- ER22-3384 Bench-Scale Demonstration of Per-and Polyfluoroalkyl Substances (PFAS) (Destruction in Solids Using Supercritical Water Oxidation (SCWO)
- ER21-5119 On-Site Demonstration of Thermal Desorption Coupled with Thermal Oxidation Technology to Treat Solid PFAS-impacted Soil Investigation Derived Waste
- ER20-3044 Thermal Reactivation of Spent GAC from PFAS Remediation Sites
- ER22-4014 Thermal Treatment for Effective Per- and Polyfluoroalkyl Substances Decomposition in Solid Matrices and AFFF Concentrate

12.8 Integrated Water Treatment Solutions

This section provides guidance on the development and selection of treatment solutions for water containing PFAS in combination with other constituents. It is often necessary to combine treatment technologies into integrated solutions to achieve project objectives for co-contaminants. While PFAS can affect multiple media, the focus of this section is on treatment of water and the water treatment processes. The water matrix may contain constituents such as TOC, TSS, and TDS at levels that may require pretreatment because they could interfere with and reduce the effectiveness of the PFAS treatment technologies. Regulated organic and inorganic co-contaminants require treatment to meet their respective remedial objectives. An integrated solution can include a combination of treatment mechanisms (separation, sorption, and destruction) and development stages (for example, field-implemented, limited application, and developing).

12.8.1 Development of Alternative Water Treatment Trains

Many factors play into the development and selection of integrated treatment solutions and the considerations and examples provided here are intended to assist in the selection process. The remedial action or treatment objectives are key drivers in selecting treatment technologies and waste disposal methods. Liquid and solid waste stream generation is another critical factor in the selection process as waste may be subject to PFAS regulations. While the focus of this section is on water treatment, the treatment technologies applicable to solid wastes are discussed in Sections 12.3, 12.4, and 12.6. Factors affecting pre-treatment, primary treatment, and post-treatment selection are presented in Section 12.1.1. Selection of an integrated treatment solution may be an iterative process to select a primary treatment technology that best meets project objectives while minimizing the associated pre-treatment, post-treatment, and generated waste streams.

Figure 12-7 (provided as a separate PDF) shows a sample flow chart that includes a variety of options for integrated treatment solutions based on different water and process waste matrices. The water matrix column in the flow chart, which represents the composition of the water to be treated, includes examples of naturally occurring substances and inorganic and organic co-contaminants. The pre-treatment stage provides examples of technologies that can be used as standalone or in combination for treating different co-contaminants. The PFAS treatment system can also include multiple treatment technologies (treatment train) that each generate waste that must be subsequently treated or disposed of. The sample flow chart provides examples of wastes generated by different treatment technologies and corresponding potential disposition options. Factors in selecting PFAS treatment methods are presented in Sections 12.2, 12.3, 12.4, 12.5, 12.6 and 12.7.

Every water source is different, so proper characterization is important for developing and selecting the proper integrated solution. The following questions may help guide the selection process:

1. What are the remedial action objectives and discharge criteria for all contaminants?
2. What information is available on geochemistry, natural organic matter, and potential inorganic constituents, and what are the remaining data needs for adequate characterization?
    1. What are the pre-treatment options for the identified matrix?
    2. What wastes are generated through pretreatment?
3. What other non-PFAS organic constituents (for example, volatile and semi-volatile organic co-contaminants) are present at levels that require treatment?
    1. What types of treatment technologies or combinations of technologies apply?
    2. What wastes are generated by application of each treatment technology?
    3. Can the co-contaminants be effectively treated by the same technology as PFAS, and, if so, could this adversely affect PFAS removal? Do the technologies compete with each other, and does this reduce effectiveness and efficiency of PFAS removal?
4. Are field-implemented treatment technologies available for the treatment or destruction of waste streams; if not, consider limited application and developing technologies and possibly pilot testing?

Lu et al. (2020) provided a critical review of PFAS treatment train approaches. Additional recent work is focusing on simultaneous coupling of technologies, where PFAS are sorbed onto reactive particles, which are then destroyed in the presence of catalyst (for example, Zhang, Zhang, and Liang 2019; Xu et al. 2020). Pica et al. (2019); Soriano, Gorri, and Urtiaga (2017); and Soriano, Schaefer, and Urtiaga (2020) described and evaluated combined filtration followed by electrochemical oxidation approaches.

Related Ongoing Research Funded by SERDP:

- ER18-1230 Development, Evaluation, and Technology Transfer of BMPs for Optimizing Removal of PAHs, PCBs, PFASs, and Metals from Stormwater at DoD Sites

- ER18-1278 An Electrocoagulation and Electrooxidation Treatment Train to Degrade Perfluoroalkyl Substances and Other Persistent Organic Contaminants in Groundwater
- ER-2714 Development of Coupled Physiochemical and Biological Systems for In Situ Remediation of Perfluorinated Chemical and Chlorinated Solvents Groundwater Plumes
- ER-2718 Synergistic Treatment of Mixed 1,4-Dioxane and Polyfluorinated Chemical Contaminations by Combining Electrolytic Degradation with Electrobiostimulation
- ER18-1652 Destruction of PFAS and Organic Co-Contaminants in Water and Soil Present in Investigation-Derived Waste at DoD Sites Using Novel Adsorbent and Ultrasound
- ER21-5136 Nanofiltration Followed by Electrical Discharge Plasma for Destruction of PFAS Co-occurring Chemicals in Groundwater: A Treatment Train Approach
- ER20-1286 A Synergistic Platform for Defluorination of Perfluoroalkyl Acids (PFAAs) through Catalytic Reduction Followed by Microbial Oxidation
- ER19-1410 Treatment Train for In Situ Mineralization of PFOS Using Heat-activated Persulfate Oxidation (HAPO)
- ER18-5015 Removal and Destruction of PFAS and Co-Occurring Chemicals from Groundwater via Extraction and Treatment with Ion Exchange Media, and On Site Regeneration, Distillation, and Plasma Destruction
- ER18-1482 Chemical Decomposition Combined with Physical Adsorption for the Treatment of Investigation-Derived Waste Containing PFASs
- ER18-1633 Lines of Evidence to Assess the Effectiveness of PFAS Remedial Technologies
- ER18-1306 Combined In Situ/Ex Situ Treatment Train for Remediation of PFAS-Impacted Groundwater
- ER18-1289 Treatment of Legacy and Emerging Fluoroalkyl Chemicals in Groundwater with Integrated Approaches: Rapid and Regenerable Adsorption and UV-Induced Defluorination
- ER18-1497 High-Performance Treatment of PFASs from Investigation-derived Waste: Integrating Advanced Oxidation-Reduction and Membrane Concentration
- ER-201729 Field Demonstration to Enhance PFAS Degradation and Mass Removal Using Thermally-Enhanced Persulfate Oxidation Followed by Pump-and-Treat
- ER22-3415 Novel Swellable Ionomers for Enhanced PFAS Sorption and Destruction
- ER22-3124 A New Concept of “Release-Capture-Destruction” to Enable Remediation of PFAS in Source Zone Soils
- ER22-3150 Engineering an “All-In-One” Biochar-Surfactant System for Enhanced PFAS Sorption and Reductive Degradation Using a Coupled Ultraviolet and Ultrasonication Approach

12.9 Sustainability of PFAS Treatment

Federal and state environmental protection agencies have published myriad green remediation best management practice fact sheets and guidance documents covering a variety of remediation topics and emphasizing the minimization of environmental cleanup footprints (USEPA 2012, 2018), including methods to quantify the environmental footprint (USEPA 2019). The best management practice fact sheets for excavation and surface restoration, implementing in situ thermal technologies, and (more generally) materials and waste management may offer supplemental sustainability information to that already included alongside the remediation technologies presented within this section (USEPA 2008, 2012, 2013).

Applying such a framework for PFAS cleanup projects, the environmental impact drivers for PFAS cleanup technologies that should be considered include the life cycle environmental footprint of all facets of the cleanup, including project site preparation; installation of the remedy; materials, equipment, and energy used to operate the remedy; waste materials generated by the cleanup technology; and demolition and deconstruction of the remedy. In alignment with greener cleanups, green and sustainable remediation recommends the “the site-specific employment of products, processes, technologies, and procedures that mitigate contaminant risk to receptors while making decisions that are cognizant of balancing community goals, economic impacts, and environmental effects” (ITRC 2011, 2011, p. 3). Economic and quality of life impacts to the community can be alleviated by early incorporation of green and sustainable remediation best management practices, including meaningful stakeholder engagement, creation of employment opportunities, and advancement of the local community’s skill set to help manage treatment systems and public outreach (USEPA 2012). Lastly, climate change vulnerability and adaptation measures of remedial technologies should also be considered to ensure resiliency in the implemented remedial action (USEPA 2013, 2014).

In alignment with sustainability principles, performance of early and meaningful risk communication can assist professionals in raising the community’s awareness of environmental hazards, empowering community participation in risk reduction measures, and increasing the quality of life for the community impacted by contamination and related risk management activities (USEPA 2007). Several environmental and public health regulatory agencies have prepared information documents to assist professionals in performing effective risk communication for PFAS sites, for example, see ATSDR (2018).

In addition, a communication plan can be developed to assist with information dissemination and stakeholder engagement (Emmett et al. 2009). Section 14 provides further in-depth guidance on risk communication planning and performance. A risk communication toolbox is also being developed to help decision makers through the planning process and provide tools to assist with meeting performance metrics at each planning step. Additional guidance on stakeholder concerns and engagement is provided within this document in Section 13.

12.10 Improving Evaluation of PFAS Treatment Technologies

Significant effort has been completed with respect to reviewing and compiling comparative information on PFAS treatment technologies. In a number of instances, proponents of innovative treatment technologies have claimed success in removing or destroying PFAS with limited confirmation of performance. For example, removal mechanisms may not have been proven, byproducts may not have been measured, and the effect of the technology in actual environmental matrices, at environmentally relevant concentrations, on PFAS mixtures, or with co-contaminants present may be unknown.

To guide future assessments and investments in developing PFAS treatment technologies, a SERDP project has prepared suggested lines of evidence, recommended metrics, and decision tools to assess the effectiveness of PFAS treatment technologies. These lines of evidence and decision-making tools can be used to identify priorities and next steps to advance a given technology, assess whether a technology is ready for field demonstration, and identify key areas of uncertainty regarding technology performance.

Further SERDP-funded work (ER18-5053) is focused on developing a comprehensive assessment framework for ex situ PFAS treatment technologies and generating data to compare established and emerging approaches on a life cycle assessment and costing basis.

Related Past, Ongoing, and Recent Research Funded by SERDP:

- ER18-1633 Lines of Evidence to Assess the Effectiveness of PFAS Remedial Technologies
- ER18-5053 Evaluation and Life Cycle Comparison of Ex Situ Treatment Technologies for Per- and Polyfluoroalkyl Substances (PFASs) in Groundwater

Updated September 2023.

13 Stakeholder Perspectives

This section identifies the concerns of stakeholders who have been or may be affected by PFAS contamination. In this section, we summarize many of the concerns that have been expressed by local communities, tribes, and environmental groups. Evaluation of exposure levels and potential human health consequences are of paramount concern to stakeholders.

Section Number	**Topic**
13.1	Stakeholder Concerns
13.2	Specific Tribal Stakeholder Concerns
13.3	Stakeholder Resources

The term "stakeholder" is defined broadly by ITRC as members of environmental organizations, community advocacy groups, tribal entities or other citizens' groups that deal with environmental issues, or a concerned citizen who is not a member of any organization or group. Public stakeholders, such as advocacy groups, often speak for the communities that are affected by environmental issues. In this document, a differentiation is made between public stakeholders and interested parties (responsible parties, state regulators, and owners and operators of contaminated sites).

Stakeholders share greater ownership of outcomes when they have the opportunity to influence site characterization, remedy selection, and long-term site management. Because PFAS are so abundant in consumer products, stakeholders are also concerned with the production and eventual use of these products and are seeking safer alternatives and sometimes outright bans (see Section 2.5 for information about PFAS Uses and information about certifications related to reduction or elimination of PFAS in products). Environmental regulators and responsible parties also benefit from informed, constructive stakeholder involvement because it can help them make better decisions, reduce the likelihood of costly, time-consuming repeated work, and allow those in affected communities to have a voice in governing the long-term use of land, water, and other resources. Often, stakeholders such as long-time residents have unique site knowledge as well as a major stake in the remedial outcome. In the case of PFAS, many national environmental organizations have made community outreach a major focus. Local grassroots organizations and one, the National PFAS Contamination Coalition (https://pfasproject.net), have led a major effort to inform the public and influence policy. In addition, ATDSR studies (for example, ATSDR 2022) and National Academy of Science (NAS 2022) studies have included community outreach efforts.

Developing site-specific characterization and remediation strategies for communities and tribal organizations can be challenging, because there are many misconceptions about PFAS. The lack of scientific knowledge about many of these PFAS further enhances the need to educate the public. Therefore, early and effective community engagement emphasizing timely access to test data, transparency, and responsiveness is imperative. Community engagement may be able to address many stakeholder concerns and help to communicate risks. The ITRC Risk Communication Toolkit for Environmental Issues and Concerns includes information about stakeholder engagement and is published as a separate document. Section 14 addresses tools for PFAS-specific risk communication challenges, and provides some examples of PFAS risk communication issues.

This section identifies the concerns of stakeholders who have been or may be affected by PFAS contamination. Because PFAS are emerging contaminants and have been detected in ecological receptors (animals and plants, see sections 5.5 and 5.6) and blood serum in many humans (Section 7.1), there are many individuals who are potentially affected worldwide.

In this section, we summarize many of the concerns that have been expressed by local communities, tribes, and environmental groups. Evaluation of exposure levels and potential human health consequences are of paramount concern to stakeholders. The list of concerns below is not all inclusive, as developments in science and identification of contaminants in the environment are likely to lead to additional concerns. This list was developed from general research on PFAS, direct communication and involvement with environmental and community groups, a consultant for one of the tribes, and extensive review of news reports. **This section is intended to highlight the concerns that have been expressed by various groups. It is not intended to be a definitive statement of the technical merits of those concerns.**

USEPA conducted five community engagement events and one event with tribal representatives during the summer of 2018. Meeting materials, information, and summaries of each event are provided on USEPA's website: https://www.epa.gov/pfas/pfas-community-engagement. Series-specific lists of concern and associated social factors identified from presentations by public and community stakeholders during the USEPA PFAS community meetings held in 2018 are provided in the ITRC Risk Communication Toolkit for Environmental Issues and Concerns which is published as a separate document, and are discussed in Section 14.3.4. See also https://pfascommunityengagement.org for information about EPA virtual listening sessions in Spring 2023.

The following concerns were identified during preparation of this document, with details of these concerns in the following sections.

• Lack of comprehensive regulatory standards or advisories for thousands of PFAS for the following (13.1.1): Drinking water (13.1.1.1) Environmental media other than drinking water (13.1.1.2) Human consumption of food (13.1.1.3) Ecological risk (13.1.1.4)	• Limited availability of information on the health effects of PFAS (13.1.15)
• Desire for one standard or screening level for PFAS (13.1.2)	• Responsibility for sampling and treatment on private property (13.1.16)
• Lack of Occupational standards (13.1.3)	• The potential for PFAS emissions from cleanup methods (13.1.17)
• Lack of comprehensive monitoring information (13.1.4)	• Lack of scientific evidence that current PFAS treatment and disposal methods and remedies are fully protective of human and ecological health and prevent toxic emissions (13.1.18)
• Need to apply a precautionary approach in decision making (13.1.5)	• Stormwater and PFAS manufacturing discharges that may contain PFAS (13.1.19)
• Safety of short-chain substitutes (13.1.6)	• Psychological effects (13.1.20)
• Contamination from AFFF release sites (13.1.7) and unused AFFF disposal (13.1.8)	• Economic consequences of local PFAS contamination (13.1.21)
• Duty to warn AFFF responders (13.1.9)	• Remediation of PFAS with other contaminants, especially chlorinated solvents (13.1.22)
• Limitations in sampling and analysis methods (13.1.10)	• Pesticides containing PFAS (13.1.23)
• Limited programs for health monitoring and blood testing (13.1.11)	• Artificial turf (13.1.24)
• PFAS in food packaging (13.1.12)	• Semiconductor manufacturing (13.1.25)
• Potential PFAS contamination in recycling, compost, and fertilizer (13.1.13)	• Remediation using monitored natural attenuation (MNA) (13.1.26)
• Lack of disclosure by product manufacturers (13.1.14)	• Environmental justice (13.1.27)

Stakeholders who use this document should consider that much of the information is very technical. Nevertheless, it aims to lay a framework by which to understand this set of compounds, the foundational nature of the science, and many of the uncertainties.

13.1 Stakeholder Concerns

13.1.1 Lack of Comprehensive Regulatory Standards or Advisories for Thousands of PFAS

This section discusses the lack of advisory standards or screening values for various environmental media and exposure pathways.

13.1.1.1 PFAS in Drinking Water

In June 2022, USEPA issued interim health advisories for PFOA and PFOS in drinking water (USEPA 2022). These replace the values USEPA issued in 2016 (USEPA 2016, 2016), and are subject to change upon finalization of a National Primary Drinking Water Regulation (NPDWR) that proposes MCL and MCLG values currently under review (USEPA 2023[2644]).

Several states have regulatory values for some specific PFAS, but the majority of PFAS are not included in any of the states' regulations. Information about available current regulatory standards and guidance values for PFAS in drinking water are provided in Section 8, with a summary table linked on the PFAS fact sheet page.

Stakeholders are concerned because the health consequences of these other compounds remain uncertain. Firm conclusions relating individual PFAS to specific health outcomes remain elusive (Guelfo et al. 2018). Information about health impacts for other PFAS is provided in Section 7.1.

13.1.1.2 PFAS in Environmental Media Other than Drinking Water

With the exception of regional soil screening levels for a limited number of PFAS (USEPA 2023), there are no federal standards or screening levels for evaluating environmental media (air, soil, and surface water and groundwater not used for drinking) and limited federal requirements that compel such monitoring at the time of publication.

USEPA has developed interim recommendations for screening and remediation of groundwater for PFOS and PFOA at CERCLA and RCRA regulated sites (USEPA 2019). Section 8 includes information about regulations, guidance, and advisories for PFAS. In addition, the Water and Soil Regulatory and Guidance Values Table Excel file is available.

There are few limits by the federal and most state governments on PFAS in biosolids being applied to land for food and/or nonfood crops. PFAS, such as PFOA and PFOS, have been detected in biosolids produced at wastewater treatment plants (WWTPs), and in soil, surface waters, and leachate from landfills. WWTP biosolids are commonly applied to land as a soil amendment, and can remobilize PFAS to other migration and exposure pathways. Stakeholders are concerned about uptake by crops eaten by humans and animals. Section 2.6 introduces PFAS sources at landfills and WWTPs, and Section 5.6 and Section 6.5.1 discuss plant uptake of PFAS. USEPA will be performing a risk assessment of biosolids as part of the PFAS Strategic Roadmap (USEPA 2021).

There are few regulatory or guidance limits for PFAS in surface water that may affect fish and consumers of fish. In addition, PFAS in surface water also creates an exposure pathway that potentially affects ecological and human health. For more information on PFAS in surface water, see Section 16.

While recognizing that drinking water is the dominant exposure pathway, Vestergren and Cousins (2009) identified that PFAS impacts to other media need to be considered because "there is a clear need of investigations of how to remediate the hotspot areas with focus on the unsaturated zone," because "PFAS that are pooled in the unsaturated zone will continue to infiltrate and spread from contaminated areas as long as the source is not removed, or infiltration of precipitation is inhibited."

13.1.1.3 Human Consumption of Food

Many stakeholders want clear advisories or standards on PFAS in food due to the occurrence of PFAS in a variety of food. In Europe important sources of human exposure to PFOA and PFOS have been found to include the consumption of fish, meat, and eggs (EFSA 2018). The US Food and Drug Administration (FDA) has published information on their PFAS studies on their website (USFDA 2019[1768]). Few screening levels or advisories have been posted; for example, Maine has developed screening levels for fish for PFBS, PFOS, and PFOA, and for milk and beef for PFOS (ME DEP 2021). Further information about development of standards for food consumption is found in Section 8.2.2.11. PFAS are found in a variety of foods, including homegrown produce and wildlife. Some areas of concern regarding foods include the following:

- PFAS have been found in food purchased at stores. Some occurrence information for foods collected as part of the FDA's Total Diet Study is published in Genualdi et al. (2021).
- Some states have issued fish consumption advisories for specific lakes and rivers after tests confirmed the presence of PFAS in surface water. Section 15.3 includes a case study example about a recently enacted fish consumption advisory by the New Jersey Department of Environmental Protection.
- In February 2018, the Environmental Protection Authority of Victoria, Australia, "assessed waterfowl from three wetlands to better understand the extent and distribution of PFAS contamination ahead of the duck hunting season. PFAS was detected in waterfowl from all three wetlands." As a result, health risk assessments were undertaken and human health advisories were issued (Environmental Protection Authority Victoria 2019), p.1).
- In Wisconsin, the Department of Natural Resources (DNR) recommended not consuming the liver of deer killed within a 5-mile radius of an industrial site where elevated levels of PFOS were found. "DNR And DHS Issue Do Not Eat Advisory for Deer Liver In Five-Mile Area Surrounding JCI/Tyco Site In Marinette", September 15, 2020, https://dnr.wisconsin.gov/newsroom/release/37921.
- Alaska Community Action on Toxics (ACAT) (Byrne 2009) reported that "A study by Martin et al. (2004) on the presence of PFOS in the livers of arctic animals revealed elevated PFOS levels in almost all species studied." Furthermore, it reported that "In a recent study (Ostertag et al. 2009[2119]) of foods consumed by a Canadian Inuit population, traditional foods were more widely contaminated and contained higher concentrations of PFCs [PFAS] than nontraditional foods. Caribou had the highest concentrations of perfluorinated compounds (PFCs), including PFOS." At the request of the Yupik people of St. Lawrence Island, the ACAT is conducting a study to determine the safety of the traditional foods they eat for subsistence (Byrne 2009).

13.1.1.4 Ecological Risk

There is wide stakeholder concern that ecological receptors have been or will be harmed by releases of PFAS to the environment (Section 7.2). Currently, there are no federal risk-based ecological guidelines or thresholds for environmental media. Ecotoxicity studies are generally limited to a relatively small number of PFAS (typically PFOA and PFOS). Stakeholders are asking for expanded studies in this field to evaluate additional PFAS, including short-chain precursor compounds as well as "next-generation" substitute compounds. Several states have established some criteria that are intended to protect aquatic organisms in their respective surface waters (see Section 16.3).

13.1.2 Desire for One Standard or Screening Level for PFAS

Among stakeholders there is a difference of opinion regarding how standards for PFAS should be established. Many stakeholders believe that PFAS should be treated as a class of chemicals (Kwiatkowski et al. 2020), similar to how PCBs or dioxin are currently regulated. In 2021, Vermont concluded that further information is needed to evaluate the feasibility of regulating PFAS in drinking water as a class (VT ANR 2021,2021). Section 7.1 includes information about approaches for assessing toxicity of PFAS mixtures.

Given the lack of toxicological information for the vast majority of PFAS, when even less is known about the potential additive and synergistic effects associated with PFAS mixtures (see Section 7.1.5), many stakeholders support evaluating the mass of total PFAS as a preferred screening method, rather than limited compound-specific testing using target analyte lists (CSWAB 2018). However, it is noted that given the lack of a method to test for total PFAS (see Section 13.1.10), screening might need to be completed using a method such as the TOP assay, total organic fluorine, or non-target analysis as descried in Section 11. For example, the Conservation Law Foundation in New England put forth a petition requesting that PFAS in drinking water be regulated as a group with a treatment technique drinking water standard. See https://www.nhpr.org/post/activists-ask-new-england-states-regulate-pfas-chemicals-class#stream/0 and https://www.mass.gov/lists/pfas-information-a-petition-for-rulemaking-to-establish-a-treatment-technique-drinking-water. However, some interested parties do not support treating PFAS as a class of chemicals, because some PFAS, such as certain fluoropolymers, like PTFE, might need less toxicological information because they are unable to enter cells, they are not mobile in the environment, they do not bioaccumulate, and they are therefore not available to cause adverse health effects (Henry et al. 2018), although this issue needs further study (Lohmann et al. 2020[1821]). See also Section 2.2.2.1.

13.1.3 Lack of Occupational Standards

There are few standards or guidance values for occupational exposure for PFAS. NIOSH identified occupations that might have a higher potential exposure to PFAS, and identified occupational exposure studies and other research (NIOSH

2021). Stakeholders are concerned that paper mills and wastewater treatment plants where PFAS have been documented in indoor air, and manufacturers and industrial users of PFAS, do not have specific occupational standards for all of the PFAS that the workers might be exposed to during workplace activities.

13.1.4 Lack of Comprehensive Monitoring Information

Many stakeholders are concerned that most individuals and communities do not have any testing for PFAS. Moreover, there is no comprehensive federal requirement for PFAS testing of all drinking water systems and private wells. Based on publicly available data, there is an estimate that up to 80 million people in the United States might have drinking water with PFOA and/or PFOS concentrations greater than 1 nanogram per liter (Andrews and Naidenko 2020).

Limited testing has occurred in some public water systems, and USEPA's Unregulated Contaminant Monitoring Rule (UCMR) and other regulatory programs have provided more (see Section 8). Some significant points regarding the status of a comprehensive monitoring effort follows:

- As described in Section 8.2.2.4, the third round of USEPA's required monitoring program (UCMR3), which occurred between 2013 and 2015, sampled for only six of the thousands of PFAS. UCMR3 was limited to public water systems (PWS) serving more than 10,000 people and a nationally representative subset of smaller PWSs, but private wells and many smaller PWSs were not included. More information about the UCMR3 data is included in Section 8.2.2.4. From this data set, it was estimated that approximately 6 million residents of the United States have drinking water that exceeds the 2016 health advisory for PFOA or PFOS, or both (APHA 2016).
- Sampling for UCMR4 (USEPA 2016), which occurred between 2018 and 2020, did not include any PFAS in its analyte list (USEPA 2020). Many stakeholders are concerned that an opportunity to better understand the magnitude of PFAS contamination on PWSs was not taken.
- Summarizing information about the UCMR, Siros (2018) stated, "America's Water Infrastructure Act of 2018 … requires drinking water systems serving more than 3,300 people to test for unregulated contaminants pursuant to USEPA's [UCMR]. Prior to this new law, only drinking water systems that served more than 10,000 people were required to monitor for unregulated contaminants. …Th[e] new testing requirement, which goes into effect in 2021, is expected to add more than 5,000 drinking water systems to the list of systems that are required to test for these unregulated contaminants." UCMR5 testing, scheduled for 2023–2025, will analyze for 29 PFAS chemicals (for which there is a validated USEPA testing method) in systems serving more than 3,300 people using lower detection limits than previous UCMRs. UCMR5 will also include monitoring at a nationally representative subset of PWSs (approximately 800) serving fewer than 3,300 people, contingent on appropriations, (USEPA 2023). UCMR5 does not mandate sampling of private water wells (USEPA 2023).
- Some states (for example, New Hampshire, Massachusetts and Vermont) have initiated testing of private wells in certain locations where there is a high potential for PFAS contamination, and require testing of public water systems subject to maximum contaminant level (MCL) regulations. The Washington State Department of Health announced that it will be conducting additional testing for PFAS at several hundred untested water systems. The state of Michigan is also testing all public community water systems for PFAS (see https://www.michigan.gov/pfasresponse/drinking-water/statewide-survey). New Jersey requires that sellers of private homes must test the wells prior to the sale of a home, and requires that landlords test private wells every 5 years (https://dep.nj.gov/pfas/drinking-water/#is-testing-for-pfas-required-under-new-jerseys-pwta).

13.1.5 Need to Apply a Precautionary Approach in Decision Making

Given the lack of toxicological data for the great majority of PFAS and PFAS mixtures, many stakeholders want a precautionary approach to the use, treatment, and analysis of PFAS-containing chemicals. This precautionary approach presumes compounds of similar structure may be expected to have similar modes of action and pose a similar risk to human health and the environment, lacking evidence to the contrary. This is particularly true because there are many nonessential uses of PFAS in consumer products (see Section 2.5) that receive no regulatory scrutiny.

13.1.6 Safety of Short-chain Substitutes

Many stakeholders are concerned with the use of substitute short-chain PFAS. After concerns arose that PFOA and PFOS (both long-chain PFAS) have health risks at very low concentrations, industry began to substitute them with shorter chain PFAS (see Section 2.4). Although some short-chain PFAS appear to be less bioaccumulative, the publicly available data are limited. Some short-chain PFAS can be persistent, and tend to be more water–soluble and more mobile than long-chain PFAS. Because of their greater water solubility, studies indicate short-chain substitutes are more readily taken up by plants than longer chain PFAS, including food crops (Higgins 2017). In their Interim Chemical Action Plan for PFAS, the Washington State Department of Ecology and Washington State Department of Health (2019 p. 1) states that short-chain PFAS are difficult to remove from water, noting further, “Without additional health and safety data, it is impossible for us to evaluate whether short-chain replacements are safe substitutes. If environmental exposures to short-chain PFAS are found to pose health risks to people or the environment, mitigation will be difficult and expensive.” Precursor compounds for some short–chain PFAS are also of interest in future monitoring studies; for example, perfluoro-1-butane-sulfonamide (FBSA, a precursor to PFBS), has been documented with high detection frequency (32 out of 33 samples) in fish from North America (Chu et al. 2016; Ericson, Jogsten, and Yeung 2017). Finally, in the Helsingør Statement (Scheringer et al. 2014) and the Madrid Statement on Poly- and Perfluoroalkyl Substances (Blum et al. 2015), scientists and other professionals expressed concerns about the embrace of short-chain PFAS as preferable replacements for long-chain PFAS.

13.1.7 Contamination from AFFF Release Sites

Many stakeholders believe that all potential AFFF release sites should be investigated, and where necessary, potential exposure should be mitigated. Investigations to date have identified the use of AFFF as one of the main sources of PFAS releases to the environment, and AFFF releases have been responsible for PFAS contamination of multiple drinking water sources. Although AFFF foams typically contain less than 2% total PFAS, thousands of gallons of foam mixture may be applied during a given event, and the concentrations of concern for PFAS are very low (below 100 parts per trillion (ppt)). Typical locations where AFFF is stored and used include civilian airports, military bases, chemical plants, municipal fire departments, oil refineries, bulk fuel storage facilities and terminals, and crash sites. AFFF was used abundantly for training purposes at military bases with flight operations and at civilian airports. Additional information is presented in the ITRC AFFF fact sheet and in Section 3.

13.1.8 Contamination from Unused AFFF Disposal

Stakeholders are concerned that incineration of unused AFFF is not always specifically regulated with PFAS-specific emission conditions and limits, and that incineration may generate dangerous byproducts (see Section 3.10 on AFFF Disposal; USEPA 2020; Earthjustice 2020). The U.S. military indicated plans to collect and destroy unused firefighting foam that contains PFOS and PFOA (USDOD 2018). In a 2017 request for AFFF disposal research project proposals (U.S. Air Force 2017), the Air Force acknowledged that the foam, which was designed to resist extremely high temperatures, is difficult to burn and that “the high-temperature chemistry of PFOS and PFOA has not been characterized, so there is no precedent to predict products of pyrolysis or combustion, temperatures at which these will occur, or the extent of destruction that will be realized.” Stakeholders are concerned that there are no federally mandated protocols that require incineration to reach certain temperatures to specifically target PFAS. (See https://theintercept.com/2019/01/27/toxic-firefighting-foam-pfas-pfoa/)

The National PFAS Contamination Coalition (an assembly of stakeholder groups from across the U.S.) opposes incineration (and similar thermal treatment technologies) for disposal of PFAS-contaminated wastes and collected PFAS products because stakeholders are concerned that thermal treatment technologies may not be specifically permitted to treat PFAS, and that demonstration is needed that treatment will fully destroy PFAS, that is, reduce the molecules to carbon, fluoride salts, and/or other constituents (National PFAS Contamination Coalition Statement on Incineration of PFAS – National PFAS Contamination Coalition (pfasproject.net)). See Section 13.1.18 below.

The USEPA’s Interim Guidance on Destroying and Disposing of Certain PFAS and PFAS-Containing Materials That Are Not Consumer Products (USEPA 2020) indicates that thermal treatment (which includes incineration) is commercially available and potentially has the capability to destroy PFAS or manage the migration of PFAS in PFAS-containing materials, but that further research activities are needed. Some facilities in the United States have been permitted by state regulatory agencies for the thermal treatment of PFAS.

The Foam Exposure Committee (FEC), a subgroup of the Fire Department Safety Officers Association (FDSOA 2021), whose objective is to reduce firefighter/first responder exposures to PFAS in firefighting foams, reports that the absence of federal and state regulations addressing disposal provides more opportunities for fire departments to expose their firefighters and contaminate their own communities with AFFF products. Current regulatory programs that address use and disposal of AFFF are provided in Section 8.2.

13.1.9 Duty to Warn AFFF First Responders

Aside from standard workplace safety requirements regarding hazardous materials right-to-know, stakeholders are concerned that there has been no legal duty to warn or to require notice of hazards to first responders who handle AFFF.

Several studies have concluded that some PFAS were elevated in the blood of first responders.

- The New Hampshire Department of Health and Human Services PFC Blood Testing Program (NH DHHS 2016) results indicate the geometric mean levels of PFOS and PFHxS in the blood serum of firefighters were elevated versus the geometric mean levels of those who had not worked as firefighters. Numerous other studies indicated that blood serum levels were elevated in firefighters (LeMasters et al. 2006; Jin et al. 2006; Dobraca et al. 2015). It is difficult to tease out whether these higher levels are related to exposures to AFFF, PFAS in firefighter gear (clothing), consumption of water from PFAS-contaminated drinking-water wells in affected communities, especially those that may be located near training facilities that have used AFFF, or other sources.
- IPEN (International Pollutants Elimination Network) released a report that presents information from recent studies that firefighters using AFFF have elevated blood levels of both PFHxS and PFOS; see also NIOSH (2021) for links to additional research. Earlier IPEN reports describe fluorine-free firefighting foam alternatives that can replace uses of toxic fluorinated firefighting foams (IPEN 2018, 2019). The FEC recommends replacing older stocks of AFFF with fluorine-free foam solutions (FDSA 2021).

13.1.10 Limitations in Sampling and Analysis Methods

Stakeholders are concerned that current PFAS site investigations may not adequately define the types and total mass of PFAS present, due to limitations in analytical methods (see Section 11) that are still evolving. Moreover, the PFAS family of compounds contains thousands of chemicals, but standard analytical methods can identify only a fraction of these chemicals.

A related concern is that the specification for shorter chain AFFF published by the Department of Defense (USDOD 2018; NAVSEA 2017) still allows concentrations of PFOA and PFOS up to 800 ppb in AFFF concentrate, because that is the lowest concentration of either PFOA or PFOS that can be measured in the concentrate with current analytical methods. This is because the overall high concentrations of the many chemicals in the AFFF concentrate “swamp” the lab instrument, interfering with its ability to detect any individual compound except when it is present at high concentrations. The DOD has recently published a draft analytical method, DOD AFFF01, to quantify PFOA and PFOS with a limit of quantitation of less than 25 ppb (Willey 2021). The modern short-chain AFFF formulations are fluorotelomer-based, so PFOS (and other PFSAs) should not be present and PFOA may be present only as contamination from the production process (as discussed in Section 3.1), but without analytical methods to prove this, users cannot know for certain if the new AFFF products are PFOS- and PFOA-free. The ITRC AFFF fact sheet and Section 3 include more information about AFFF specifications.

13.1.11 Limited Programs for Health Monitoring and Blood Testing

Some PFAS (for example, PFOA, PFOS) bind to proteins in the blood, making blood testing a means of investigating human exposure to PFAS (see Section 7). Many communities where PFAS have been detected have asked that the government establish a program for blood serum testing and long-term health monitoring so that they can better understand any health risks associated with PFAS exposure. ATSDR established a multi-site study with seven partners across the country to better understand the connection between PFAS exposures and health effects (ATSDR 2020).

Some states have provided limited testing on people in high-impact areas. For example, New Hampshire provided blood serum testing for people who worked on, lived on, or attended childcare on an AFFF-impacted site and were exposed to contaminated drinking water (NH DHHS 2016). New Hampshire also performed blood tests in selected towns where people used private wells that tested above the 2016 health advisories for PFOA and PFOS. However, many state and local governments are wary of blood testing programs because there is no correlation between the PFAS level in blood serum and any definitive health effects. People who participate in such tests are usually informed of their results and provided context about how they compare with national and location-specific averages. Only limited long-term programs have been established to monitor the health outcomes of exposed populations (for example, C8 Science Panel (C8 Science Panel 2020). If there is no assistance from the government, many community members cannot afford to have their blood tested.

13.1.12 PFAS in Food Packaging

Many stakeholders are concerned that food packaging containing PFAS leaches into food. Food packaging, such as bowls, plates, clamshells, trays, and pizza boxes, often includes PFAS for anti-grease resistance, and PFAS is sometimes used in the molding process to manufacture paper plates and containers. A 2008 FDA study found that “fluorochemical paper additives do migrate to food during actual package use,” and oil and grease “can significantly enhance migration of a fluorochemical from paper” (Begley et al. 2008).

There is only limited peer-reviewed information regarding PFAS transfer to food. One study documented that 6:2 FTOH moves from dishware or containers into food (Yuan et al. 2016). A Canadian analytical lab found that PFBA moves from cupcake liners into cupcakes (CEH 2018).

The FDA has approved 20 next-generation, short-chain PFAS for coating paper and paperboard used to serve food. The FDA Effective Food Contact Substance Notifications database is available online (FDA 2018). Concerns have been raised that these compounds have not been adequately tested for human impact. Because of trade secrecy laws with regard to patents, the government does not publicly disclose the identity of the specific chemicals in food packaging. However, according to The Intercept (Lerner 2016), in documents filed with the USEPA, under TSCA section 8(e) requirements, DuPont (2010) reported that substitute PFAS used to produce food contact paper could pose a “substantial risk of injury,” including cancerous tumors in the pancreas and testicles, liver damage, kidney disease, and reproductive harm. For more information about FDA’s PFAS activities and food contact materials (FCM) PFAS phaseouts, please see Section 8.2.

Although there are no enforceable PFAS limits in food or water at the federal level as presented above in Section 13.1.1.3, some states and cities are moving forward with bans. Several states, including Washington, Minnesota, Maine, New York, and Vermont, have enacted laws to ban PFAS use in some food packaging. See Section 8.2 and the Regulatory Programs Summary Excel file for information about regulatory programs. Stakeholders are concerned because not only does PFAS in food packaging pose potential risks to consumers of the food, but the used packaging may end up in compost or landfills. Compost is eventually applied to soil and PFAS are potentially transferred to certain food crops, and may leach to groundwater. If compost goes to a landfill, PFAS potentially ends up in the landfill’s leachate.

13.1.13 Potential PFAS Contamination in Recycling, Compost, and Fertilizer

Carpeting, furniture, and numerous other items containing PFAS are often recycled. There is concern that the recycled materials are often used in products where the consumer has no way of knowing whether it is has PFAS contamination. Biosolids from wastewater treatment plants are used in some composts and fertilizers and PFAS sampling may not be part of the screening process for these products. However, this is changing; New Hampshire and Maine both require testing. Additionally, stakeholders are calling for more testing and regulation for land-applied or disposed paper mill waste due to potential PFAS impacts. Stakeholders are concerned that composting of paper mill waste to make fertilizer, which, for example, is still done in Michigan, should get more attention. It is difficult to know which mills make “waterproof” or food contact papers that contain PFAS.

13.1.14 Lack of Disclosure by Product Manufacturers

Some stakeholders are concerned that chemical and product manufacturers are not required to disclose when they sell, make, or use PFAS in their products because some formulations are proprietary and may not be listed on a Safety Data Sheet. For example, many sturdy, waterproof, and heat-resistant products containing PFAS are produced for the construction industry, including polished granite countertops. Additionally, there is lack of disclosure and transparency concerning the composition of AFFF, because AFFF suppliers claim that formulations are proprietary.

13.1.15 Limited Availability on Information on the Health Effects of PFAS

Some stakeholders are concerned that politics may delay or even prevent the full disclosure of PFAS toxicity information. For example, the 2018 release of ATSDR’s Draft Toxicological Profile for PFAS was reportedly delayed because of concerns about the public response. This example, if replicated, may lead to distrust and reduce the efficacy of risk communication. Additionally, collected health data may not be clearly and fully shared or explained to stakeholders.

13.1.16 Responsibility for Sampling and Treatment on Private Property

When off-site contamination is suspected or discovered, stakeholders believe that the responsible parties should be accountable for establishing an entire program to deal with the problem. This includes sampling and analysis, disclosure of PFAS content, health monitoring, and if appropriate, remediation and mitigation. Upon detection of PFAS above state or USEPA limits, stakeholders maintain that responsible parties should be required to provide affected residents with alternative water supplies. Additionally, stakeholders believe that the cost of the program, including long-term treatment and monitoring, should be borne by responsible parties.

13.1.17 Potential PFAS Emissions from Cleanup Methods

Stakeholders believe that treatment systems (from large public water treatment systems to small private point-of-use systems) should be monitored for effectiveness, as the type and frequency of monitoring may vary for all systems. There is also concern that disposal or regeneration of GAC canisters, resins, and byproducts will add contaminant loads of PFAS to the air, land, and water. Stakeholders are concerned that companies that thermally treat spent carbon filters that contain PFAS do not provide publicly accessible information that documents full destruction of all PFAS; some companies claim all PFAS are destroyed, yet the research appears to be focused on targeted PFAS (for example, PFOS and PFOA) destruction. More concerns about thermal treatment are discussed in Section 13.1.8, with further information provided in Section 12.4.

13.1.18 Lack of Scientific Evidence that Some PFAS Treatment and Disposal Methods and Remedies Are Fully Protective of Human and Ecological Health and Prevent Toxic Emissions

Historically, the three standard practices for PFAS waste management are landfilling, wastewater treatment, and incineration. Stakeholders' concerns with these disposal practices are highlighted in a study sponsored by the Environmental Working Group (EWG) (https://www.ewg.org/news-insights/news-release/study-disposal-pfas-waste-increases-contamination). One of the conclusions of that study is that all three methods have been found to not effectively contain or destroy PFAS. Tasha Stoiber, EWG senior scientist and primary author of the study, found that "The three common 'disposal' options for getting rid of PFAS do not eliminate these contaminants but rather end up just returning either the same chemicals or their byproducts back into the environment." Additionally, USEPA has confirmed that while "Thermal treatment technologies are common remediation approaches for contaminated media and waste, limited information exists on the efficacy, potential atmospheric emissions, operational conditions, costs, etc. for thermal treatment technologies specifically targeted for PFAS" (Mills et al. 2020).

Additionally, USEPA stated that "Research on thermal stability of PFAS compounds, the ability to fully capture and identify PFAS compounds and their thermal decomposition byproducts, and the efficacy of emission control technologies are areas of targeted research. These efforts, in cooperation with states and industries, [are] aimed at proper disposal of PFAS-laden wastes without media-to-media transfer or environmental release" (USEPA 2019). In USEPA's Interim Guidance (USEPA 2020), they identified areas for further study to assess the efficacy of destruction and disposal of PFAS-containing materials (that are not consumer products) to help protect public exposure to PFAS. Recent testing and reporting of PFAS destruction by incineration has been documented (see Section 12.4).

Additionally, it should be noted that other technologies besides the three methods can be used in remediation. These include ion exchange, granulated activated carbon (GAC), and reverse osmosis (see Section 12).

An example that demonstrates the stakeholders' concerns about adequate protection provided by disposal options is the Holston Army Ammunition Plant (Holston) in Tennessee. In a July 16, 2019, letter to USEPA Region 4 Administrator (https://cswab.org/wp-content/uploads/2019/07/Holston-Citizen-Petition-Region-4-PFAS-July-2019.pdf), several environmental groups stated that Holston will present a risk to human health and the environment by burning polymer-bonded explosives (PBXs) containing PFAS. The groups cited a recent decision by the neighboring State of Kentucky to prohibit the Blue Grass Army Depot from open-air burning or detonation (OB/OD) of "munitions wastes that are a potential source of Per- and polyfluoroalkyl substances (PFAS), including Teflon, Viton, and Viton-A. This includes both short and long chain PFAS." Both bases are located in USEPA Region 4. The groups stated: "Open air burning and detonation do not provide either sufficient or sustained temperatures times to achieve destruction. OB/OD activities at Holston are very likely resulting in the ongoing release and dispersion of PFAS to the environment, posing a potentially substantial health risk to workers and residents."

13.1.19 Stormwater and PFAS Manufacturing Discharges that May Contain PFAS

PFAS, including PFOA, have been detected at the storm drain outfalls at active facilities. Stakeholders are concerned that most NPDES effluent permits do not require PFAS sampling and the magnitude of PFAS concentrations in such discharges remains unknown. Older and inactive facilities' discharge areas, many of which have not been sampled for PFAS, may also act as long-term sources of stormwater and/or groundwater contamination due to residual PFAS in soil at stormwater discharge areas.

13.1.20 Psychological Effects

It was reported at one USEPA community forum that children in some communities are scared to drink water. See the USEPA community meetings information provided on USEPA's website: https://www.epa.gov/pfas/pfas-community-engagement. This has occurred in communities where contaminated drinking water supplies have the effect of deterring children from drinking clean water. Additionally, blood level values have become an identity, and there are pictures of people holding up signs identifying their blood levels.

13.1.21 Economic Consequences of Local PFAS Contamination

Individuals have voiced concerns about significant economic consequences on property values and businesses. See the USEPA community meetings information provided on USEPA's website: https://www.epa.gov/pfas/pfas-community-engagement. In one case in Massachusetts, the Board of Health added PFAS to the list of substances homeowners with private wells in certain areas of town must test for before selling their homes (Town of Harvard, MA 2020). In New Jersey, PFOA, PFOS, and PFNA were added to a list of chemicals that private well owners must test for prior to selling their homes under the NJ Private Well Testing Act. This also applies to landlords who rent homes with private wells (see https://www.nj.gov/dep/rules/adoptions/adopt_20200601a.pdf). In another instance, because PFAS was detected in water used by dairy cattle, the farmer had difficulty selling the milk products. Stakeholders are particularly concerned about facilities located in economically disadvantaged communities. These communities need the economic benefits of a facility but have few resources to demand enough testing of air emissions and of potential health impacts on the community.

13.1.22 Remediation of PFAS With Other Contaminants Especially Chlorinated Solvents

At many sites where PFAS has been found, especially military sites that are contaminated with AFFF, there is concern that past cleanup efforts have spread PFAS. Many military sites have been listed as Superfund sites because they are contaminated with chlorinated solvents (https://www.epa.gov/fedfac). The early remedy for removal of solvents from groundwater was pump and treat with air strippers. Since air stripping doesn't remove PFAS, groundwater contaminated with PFAS was, and in some cases continues to be, discharged into streams and rivers, through reinjection, discharge to wastewater treatment plants, or reuse such as irrigation or make-up water for recycling.

Even if remediation systems use GAC or other techniques to clean up chlorinated solvents (for example, PCE and TCE), these systems are not typically optimized for PFAS capture. If they are optimized for PFAS capture, it is unclear if they will be as effective for solvent capture. Additionally, it is not clear whether in the past PFAS was released during the regeneration process for solvent-laden GAC, thus spreading some PFAS through air during the heating process. More information about treatment systems and co-contaminants is included in Section 12.8.

13.1.23 Pesticides containing PFAS

Some pesticides contain PFAS. PFAS have been used as an active and inert (or inactive) pesticide ingredient. PFAS can be used as herbicidal dispersants and wetting agents and to aid wetting and penetration in insecticides. A patent has been issued for insecticides and fungicides having branches composed of perfluoroalkyl chain molecules. Other pest control patents refer to compounds with some of the side chains composed of perfluoroalkyl (Gaines 2022). This creates a number of problems, including low levels residing in soil, uptake in food, and "masking" other sources of the PFAS in areas that have been historically sprayed with insecticides. Some pesticides have received new USEPA guidance, including https://www.epa.gov/pesticides/epa-stops-use-12-pfas-pesticide-products and https://www.epa.gov/pesticides/pfas-packaging. More information about PFAS uses is included in Section 2.5.

13.1.24 Artificial Turf

Many stakeholders are concerned that plastic grass blade and/or "rubber crumb" backing in artificial turf contains PFAS. Artificial grass blades are plastic and were found by one nonprofit organization to contain PFAS. This issue was investigated by the Connecticut Department of Energy & Environmental Protection (CH DPH 2022), which analyzed "grass" blades from a previous study and suggested that the PFAS had a different origin (see Table 2-6). While this may be true for the product analyzed, artificial turf in parks and schools is from many different manufacturers. Additionally, "[a]rtificial turf infill is often made from recycled tires, which may be another source of PFAS. Polymeric pellets manufactured specifically as infill are also available, and patents indicate that these materials may contain PFAS as well" (Fernandez, Kwiatkowski, and Bruton 2021). The City of Boston has recently banned all new artificial turf in city parks. (https://www.theguardian.com/environment/2022/sep/30/boston-bans-artificial-turf-toxic-forever-chemicals-pfas)

13.1.25 Semiconductor Manufacturing

There is concern that the semiconductor industry has long been a source of PFAS that has been overlooked. A recent survey of the technical literature by researchers from Cornell University "revealed that there are several specific examples of fluorocompounds that are currently in use by the semiconductor industry in the lithography process" (Ober, Florian, and Deng 2022). More information about PFAS use is available in reports from the Semiconductor Industry Association (SIA 2023; SIA 2023). As with the concern about remediation of PFAS with other contaminants, the manufacture of semiconductors has also seen releases of chlorinated solvents. In the remediation process, the industry used pump and treat with air stripping, which does not remove PFAS from contaminated water; thus, PFAS remained in the discharge waters. In one case (Moffett Field), the site was contaminated by a plume of chlorinated solvents that spread from a center for semiconductor development that is now commingled with the VOCs and other PFAS used at Moffett Field. Recently, NASA, which is the steward of the site, found PFAS from past use of AFFF and from the semiconductor industry adjacent to Moffett (Tetra Tech 2022).

13.1.26 Monitored Natural Attenuation (MNA) for PFAS

Although early in the research stages, using remediation techniques that employ MNA for PFAS presents a range of problems and concerns for community and tribal stakeholders. As this document points out in its discussion of these still unproven processes to remediate PFAS (see Section 12.6.7), there are no currently recognized destructive attenuation pathways for PFAAs (a class of PFAS) in natural settings. Communities generally do not favor prolonged cleanup approaches with uncertain funding, with a commensurate degree of risk, and a shift of the burden for environmental cleanup to another generation. A related stakeholder concern is that the strictest cleanup standards be applied. Cleanup standards may differ from site to site based on risk assessments, site conditions, or state regulations Additionally, many community members perceive MNA as a "do-nothing" approach.

MNA for PFAS is similar to nondestructive retention processes for metals and radionuclides, thus leaving diluted PFAS in the environment (ITRC 2010, section 5 Stakeholder and Tribal Issues). This referenced document details major concerns that are specific to leaving contamination in place, including requirements for enhanced community participation; need for long-term monitoring and maintenance; future use considerations; and long-term health and safety, as well as many tribal concerns. The framework from ITRC (2010, section 5), is used here to address stakeholder perspectives and concerns about using MNA for PFAS.

- Enhanced Community Participation

Attenuation-based restoration projects require the community to coexist with some residual level of contamination for an extended period. Attenuation-based projects should always include communicating this temporal component. Prior to beginning attenuation projects, the public must be fully informed of planned activities and potential consequences. Afterwards, stakeholders must be informed about the progress in retaining chemicals "safely" in place and the risks of long-term environmental changes that may affect the retention capability of the subsurface, such as geochemical changes in the subsurface, earth movement, and a host of natural phenomena.

- Need for Long-Term Monitoring and Maintenance

Stakeholders may be concerned that attenuation-based restoration of PFAS will require extensive long-term monitoring and maintenance to ensure that public health and ecological parameters are met. Significant uncertainties in attenuation cleanup efficacy and timelines may conflict with stakeholder expectations. Consequently, stakeholders should receive additional communication of technical information, results of monitoring, and prognoses. Stakeholders will also be concerned about what will happen if attenuation does not proceed at the projected rate. Stakeholders may expect that target contamination levels be set for future dates and for reassessment of the cleanup strategy if monitoring shows that targets are not being met by natural attenuation. As an important precept, the responsible party must commit that the remedy will be revisited (for Superfund sites, this occurs every 5 years) and selection of attenuation will not hinder future investigations and consideration of other means to remove the contaminants.

- Future Use Considerations

Generally, the public favors site cleanup that leads to unrestricted use. If unrestricted use is not possible, the smallest area possible should be set aside, and institutional and engineering controls should be incorporated into the activity (see also Section 14). If the future use does lead to unrestricted use, a long-term stewardship program must be developed to ensure that the contaminants are reduced to acceptable levels or eliminated. While MNA may be less costly than other remediation techniques, the public generally is not concerned with simply reducing the overall restoration costs; they may be more concerned with removing the contamination quickly and gaining access to the land—or lifestyle—as before the contamination occurred. As such, the public should be full partners in future land-use decisions. If MNA is selected, the site should be visibly marked and documented for long-term identification.

13.1.27 Environmental Justice

In 2022, the Environmental Working Group (https://www.ewg.org/news-insights/news/2022/05/environmental-injustice-passing-costs-forever-chemicals-cleanup) published a report that stated: “PFAS have been confirmed in the drinking water of nearly 3,000 communities and are likely to be in the drinking water of more than 200 million Americans. And studies suggest that communities with environmental justice concerns are disproportionately harmed by PFAS, who will be further harmed by any delay in cleaning up.”

13.2 Specific Tribal Stakeholder Concerns

Tribes share many concerns with other stakeholders; however, they differ from other stakeholders in several key aspects. The 573 federally recognized tribes are each culturally, governmentally, and socially unique. Some tribes view any level of contamination of their lands and natural and cultural resources as unacceptable. Many tribes have culturally significant or sacred areas, which may include springs, mountains, hunting areas, plant-gathering areas, or burial sites. When culturally significant or sacred areas are affected, traditional methodologies that nontribal environmental professionals rely on (such as the applicable exposure scenarios or factors for a risk assessment) may not be sufficient to portray the effect to a tribe. For example, some plants and animals can have tremendous cultural or religious importance to a tribe, including birds and feathers, game animals, and herbs. Many tribes sustain themselves through hunting, fishing, and gathering of foodstuffs. Additionally, many tribal cultural ceremonies include the use of water. Other areas of difference include diet (for example, some tribes consume more fish per capita) and growing crops or grazing animals on areas fertilized by biosolids from wastewater treatment facilities.

Tribes are sovereign entities that have established government-to-government relationships with federal, state, and local governments—relationships that must be recognized in the decision-making process. When a PFAS-contaminated site affects a tribe, the project timeline must include tribal approvals in addition to other typical agency approvals. Sampling, research, and services on tribal lands generally require institutional review board or tribal council approval. Each sovereign nation operates differently, ranging from tribes that have no research capacity to tribes that have a full review board with a formal application process. The initial steps in the approval process may include drafting a proposal, preparing a poster or podium presentation, and presenting to the tribal government.

Once tribal approval is granted and the project commences, the practitioner must obey tribal protocol with respect to cultural practices. The tribe may reserve the right to retain the findings in the case of exploratory research and restrict publication. Regulatory findings for water and soil concentration, level of treatment, and monitoring are first reported to the tribe’s department of environmental quality or natural resources and then forwarded to state environmental organizations and USEPA.

A Tribal PFAS Working Group was formed in 2020 to “help address and reduce PFAS in Indian Country.” The working group is comprised of members of the National Tribal Water Council, Tribal Science Council, National Tribal Toxics Council, Tribal Waste and Response Steering Committee, and Tribal Pesticide Program Council (National Tribal Water Council 2023).

Most of the concerns that tribes have are listed in Section 13.1. However, as mentioned above, there may be some distinctions that are important to tribes:

- PFAS in surface waters and lakes may have a higher level of concern when they are used for fishing, given that tribal members rely on these water bodies.
- Drinking water and irrigation water in the arid Southwest are limited, and there is heightened concern that tribes will be unduly impacted if drinking or irrigation water is contaminated. Stakeholders are concerned with lack of PFAS sampling of tribal PWSs. USEPA performed limited sampling of tribal PWS during the 2022–2023 timeframe

with no PFAS results above the detection limit (USEPA 2022; Mok et al. 2022).

- Tribal lands are often close to installations that used AFFF (notably DOD) or other industrial sources of PFAS (manufacturers, leather tanneries).
- Tribal lands are often close to installations that used AFFF (notably DOD) or other industrial sources of PFAS (manufacturers, leather tanneries).
- Where biosolids have been applied to tribal farmlands or grazing lands, there is a need to sample these tribal lands for PFAS contamination. In some cases, cities may have paid tribal communities to spread biosolids from WWTPs that may have been unknowingly contaminated with PFAS.
- Activities on and near tribal lands may have involved use of PFAS-containing chemicals that could impact tribal members working in these facilities through inhalation and dermal exposure.
- Landfills on tribal lands that accepted outside waste need to be sampled for PFAS contamination, which may be in the landfill leachate. Companies that paid a fee to the tribes to use their land managed many of these landfills. Although most required sampling, often the sampling plans did not include sampling landfill leachate for PFAS.
- A big issue facing tribes is that tribal environmental offices and budgets are typically small, and they do not have the people or money to perform appropriate site investigations to determine if they have PFAS in their community.

13.3 Stakeholder Resources

Below are a number of resources for communities available at the time of publication. These resources are websites of major environmental organizations and projects that specifically deal with PFAS. These groups aim to help environmental and community groups to better understand the issues and science around PFAS. These websites have not been reviewed for accuracy or to determine if they are up to date.

https://cswab.org/pfas/about-the-pfas-campaign/ and https://cswab.org/wp-content/uploads/2010/09/List-of-military-fire-and-crash-training-sites-2014.pdf
https://pfasproject.com (A project of Northeastern University)
https://earthjustice.org/features/breaking-down-toxic-pfas
http://www.testingforpease.com
https://www.civilianexposure.org/the-military-covers-up-the-extent-of-pfas-contamination-across-the-country-while-it-continues-to-poison-hundreds-of-communities/
https://toxicfreefuture.org/science/chemicals-of-concern/pfas-nonstick-nightmare/
http://gatehousenews.com/unwellwater/
https://www.ewg.org
PFASCentral.org
https://greensciencepolicy.org/highly-fluorinated-chemicals/
https://www.sixclasses.org/videos/highly-fluorinated-chemicals
https://www.ucsusa.org/center-science-and-democracy/preserving-science-based-safeguards/toxic-threat-pfas-contamination-military-bases
https://www.nrdc.org/experts/anna-reade/epa-finds-replacements-toxic-teflon-chemicals-are-also
https://silentspring.org/research-area/about-highly-fluorinated-chemicals-pfass
https://clu-in.org/contaminantfocus/default.focus/sec/Per-_and_Polyfluoroalkyl_Substances_(PFASs)/cat/Policy_and_Guidance/
https://theintercept.com/2019/09/19/epa-new-pfas-chemicals/
https://stories.usatodaynetwork.com/unwellwater/foam-1995/
https://www.ewg.org/pfaschemicals/what-are-forever-chemicals.html
https://pfas-exchange.org
https://silentspring.org/project/women-firefighters-biomonitoring-collaborative
https://www.epa.gov/pfas/basic-information-pfas
https://health.ri.gov/water/about/pfas/
https://www.fdsoa.org/resourcepage (click on resources)
https://chemsec.org/app/uploads/2023/04/Check-your-Tech_230420.pdf

Updated September 2023.

14 Risk Communication

The PFAS Team developed a training module video with content related to this section, it is the Risk Communication video. In addition, ITRC developed a Risk Communication Training Workshop and has posted a recorded version for online viewing.

The ability to communicate potential risks to human health and the environment is a vital skill to facilitate community participation and decision-making. The process of informing people about potential hazards to their person, property, or community (Hance, Chess, and Sandman 1991; USEPA 2022) is called risk communication. Risk communication can be particularly challenging when dealing with science that is rapidly evolving, as in the case with PFAS. Communicators must grapple with competing interpretations of uncertain science and risk management strategies, while earning community trust and promoting meaningful engagement. This section addresses PFAS risk communication challenges and risk communication tools with PFAS-specific examples. Case studies that demonstrate successful risk communication planning and performance are included in Section 15.4.

Section Number	**Topic**
14.1	Role of Risk Perception
14.2	Risk Communication Challenges
14.3	Risk Communication Planning and Engagement Tools

According to USEPA's Risk Communication in Action: The Risk Communication Workbook (USEPA 2007, p.1), the overall purpose of risk communication is *to assist affected communities [to]* ***understand*** *the processes of risk assessment and management, to* ***form*** *[scientifically valid]* ***perceptions*** *of the likely hazards, and to* ***participate*** *in making decisions about how risk should be managed*. Risk is the relationship between the probability of harm associated with an activity and vulnerability of exposed elements (Slovic 1987; Slovic 2003).

The ITRC Risk Communication Toolkit for Environmental Issues and Concerns is published as a separate document. In addition, guidance on general performance of risk communication for contaminated sites is provided in *Risk Communication in Action, the Risk Communication Handbook*, (USEPA 2007); *Decision Making at Contaminated Sites: Issues and Options in Human Health Risk Assessment*, (ITRC 2015); and *Improving Dialogue with Communities: A Risk Communication Manual for Government*, New Jersey Department of Environmental Protection, (Hance 1991).

The following subsections present risk communication challenges of PFAS and provide PFAS-specific risk communication information for components of risk communication planning.

14.1 Role of Risk Perception: Public Stakeholders and Decision Makers

It is essential for decision makers to understand stakeholders' risk perceptions of the hazard. Risk perception is the disposition that individuals or communities adopt toward hazards and is the product of their knowledge, beliefs, attitudes, judgments, and feelings, as well as wider cultural and social factors. Stakeholders include, but are not limited to, the community, public entities, potential responsible parties, regulatory agencies, and municipal and state officials. Risk perception for PFAS is challenging to address because the science is rapidly evolving, the exposure is perceived as involuntary, the risk mangagement strategies are a moving target, and health impacts are greatest for the most sensitive populations. The risk management strategies can be a moving target because of these challenges.

The environmental management community is acting largely based on growing evidence of health risks and general precaution as our understanding of PFAS exposure and associated risk is continuously redefined. In this context, risk amplification (heightened perception of risk) and attenuation (diminished perception of risk) can serve as guiding principles to better understand stakeholder context and site-specific factors contributing to stakeholders' perceived risk to proposed risk management strategies. Risk amplification occurs when stakeholders perceive more risk from a hazard than the decision maker's perceived risk. Conversely, risk attenuation describes scenarios where decision makers perceive heightened risk from a hazard while stakeholders perceive less risk from the same hazard. For more information on factors that influence risk amplification and attenuation, see section 2.8 of the Risk Communication Toolkit.

14.1.1 Role of Risk Perception and Public Stakeholders

In a scenario of risk amplification, stakeholders perceive their risk to a hazard as a major concern while experts assess the hazard as carrying a lesser degree of risk (for example, low or moderate) (Kasperson and Kasperson 1996). In the context of PFAS, risk perception is heightened by uncertainties and variability among policies and standards due to developing sampling methodologies and analytical procedures; new scientific information on health effects, risk assessment evaluations, and treatment technologies (NGWA 2017); and overall confidence/trust in the proponent or lead organization that is communicating risk. Additional human health and exposure factors that heighten risk perception for PFAS are summarized in Section 14.2. Section 13 includes information about stakeholder perspectives on PFAS concerns.

This heightened sense of risk may result in opposition to proposed risk management strategies, such as source control (in which there is scientific uncertainty pertaining to the "safe" level of exposure, if any, without risk).

To address risk amplification challenges, it is important to build trust among the community by maintaining transparent communication of these uncertainties and variabilities early in the project life cycle (USEPA 2005, 2007). New data findings and research on PFAS should be regularly shared with impacted stakeholders. Current knowledge, including uncertainties and information about variability of potential susceptibility to health effects in individuals with the same exposures, should be conveyed accurately in an understandable manner.

Uncertainties in individual causation and variability in regulatory guidance can cause the affected individuals to lack confidence in current scientific knowledge. Therefore, a risk communication project team should communicate these uncertainties to the affected individuals in collaboration with risk assessors, community involvement coordinators, and community members to develop site-specific messaging. It is important to understand that standards for the same chemical often differ depending on the entity setting them. This is not unexpected, because standard-setting guidance is not simply a mathematical formula. Risk assessment approaches used in standard-setting processes include best professional judgment in the selection of the factors involved. In addition, a collaborative effort can be made to develop performance metrics, supplemental to cleanup standards, that evaluate how the action will lead to measurable increased protection for public health and the environment, thus leading to the development of targets or objectives (Hadley, Arulanantham, and Gandhi 2015) that offer reductions in risk. These metrics are referred to as secondary risk management performance metrics and can be used to communicate and evaluate success of a proposed PFAS risk management strategy, as well as assist with alleviating stakeholder concerns associated with uncertainty. Examples of applicable secondary risk management performance metrics in the context of PFAS are reduction in contaminant bioavailability/loading, source control/removal, and mitigation of exposure pathways (NGWA 2017; Harclerode et al. 2016).

Furthermore, risk amplification can be heightened when a community perceives that they have limited control over risk. Explicit efforts to share control reduce outrage and risk amplification (Sandman 2013). Therefore, it is essential to create an atmosphere of collaboration. In situations where an open public forum is met by public outrage, it important to be compassionate and lend a listening ear. Acknowledgment and documentation of questions that cannot be answered communicates transparency and can be a first step toward building trust. Effective participation is presented in the ITRC Risk Communication Toolkit for Environmental Issues and Concerns.

In contrast, in a risk attenuation scenario, experts judge hazards as relatively serious while stakeholders do not pay attention or pay comparatively little attention to that risk event (Kasperson and Kasperson 1996). This diminished sense of risk results in challenges in stakeholder participation in risk mitigation activities ("Why do we need to spend money/do testing, etc., for this?"). In the context of PFAS, risk mitigation and monitoring measures include participation in blood testing, installation of a water treatment system, and use of an alternate water source. To address risk attenuation challenges, site-specific risk perception factors related to inaction can be identified via stakeholder engagement and integrated into a communication plan (NGWA 2017; Harclerode et al. 2015; Harclerode et al. 2016).

14.1.2 Role of Risk Perception and Decision Makers

Due to the evolving science of PFAS, project managers, risk assessors, and risk communicators can also become caught in between those who amplify risk and those who deny risk. As noted, uncertainty in the toxicity and risk can lead to lack of consensus on how to evaluate risk and proposed risk management strategies. Due to risk amplification, there may be an elevated demand to take action to reduce potential risks beyond what is even technically and/or financially feasible. The underlying uncertainty feeding this risk amplification may also lead to opposition to proposed risk management strategies from some decision makers prior to establishment of the "right number" to dictate such action. When communicating with the public, it is essential to mitigate downplaying or embellishing risk due to lack of consensus on risk among decision makers.

Strategies should be implemented by the lead organization to navigate this rift to craft an approach and communicate a plan that is most likely to be reasonable and protective. One strategy is to incorporate the community's needs and values to place a greater weight on how risk management is considered. A second strategy is to develop secondary risk management objectives to help evaluate how interim and long-term action will lead to measurable increased protection for public health and the environment (Hadley, Arulanantham, and Gandhi 2015; Harclerode et al. 2016). These complexities highlight the importance of formulating a robust risk communication plan and team, including community and third-party involvement, as needed, as well as considering the dimension of perception as part of the risk communication process.

Case studies that showcase implementation of meaningful and effective community participation and inclusion of a third, neutral party to facilitate implementation of a successful risk communication strategy for PFAS-impacted communities are included in Section 15.4.

14.2 Risk Communication Challenges

There are many general challenges to risk communication about any environmental situation, including diversity of audience backgrounds, importance of establishing trust among the parties, and clearly communicating about the scientific and regulatory requirements. ITRC's Risk Communication Toolkit for Environmental Issues and Concerns includes a more detailed discussion of these challenges.

Emerging contaminants, and more specifically PFAS, pose unique challenges to achieving meaningful and effective risk communication. There is often divergent information available from different sources about the potential severity and uncertainty associated with exposure and adverse health impacts that may result from exposure, and the need for treatment or response actions. For example, people will do their own research, which may result in conflicting information. Communicators need to be prepared to explain the choices and decisions made regardless of the conflicting information. Some of the risk communication challenges for PFAS are discussed in the following sections.

14.2.1 Regulatory

There are regulatory challenges for emerging contaminants, see Section 8.

- PFAS are emerging contaminants, which means that they are the subject of intensive investigation, so new information, and thus our understanding of hazard, exposure, and risk, are emerging and evolving. This can challenge us to rethink determinations of protectiveness within very short time scales. More information is available from USEPA (2023, 2022) about PFAS and emerging contaminants.
- Federal and state standards, guidance, and policies for PFAS are not uniform and are available for only a handful of compounds. This is also challenging given the recent expansion of additional PFAS analytes added to the USEPA Fifth Unregulated Contaminant Monitoring Rule (UCMR5) (USEPA 2023), recent development of proposed federal maximum contaminant levels (MCLs) (USEPA 2023), and the lack of consensus-based toxicity values for all PFAS analytes (see Section 7.1 for information about human health effects).
- Regulatory standards and health advisories are in the parts per trillion range (or parts per quadrillion range), and it is difficult to explain to general audiences what these levels mean in terms of risk, how they were derived, or that, with current analytical methods, may not be detected.
- Most people have little to no understanding of risk assessment, risk management, and existing rules and legislation associated with chemical use and release. Risk communicators often need to provide this context before even discussing site or chemical specifics.

14.2.2 Fate and Transport

There are technical and scientific challenges and uncertainties around fate and transport of PFAS in the environment, see Section 5.

- There are many sources for PFAS and many of them have multiple release mechanisms, so simply explaining where the PFAS came from, including personal/lifestyle-based choices of individuals, and how PFAS got into the environment can be complicated.
- Most people have only a very basic understanding of (and lots of misconceptions about) chemistry, geology, environmental systems, and groundwater. Risk communicators often need to provide this context before even discussing site or chemical specifics.
- Fate and transport behaviors differ among individual PFAS (although broad generalizations may be appropriate based on chain length and functional groups).
- The environmental persistence, solubility, and mobility of PFAAs can result in:
    - very large impacted areas encompassing a wide range of environmental settings and potential transport pathways
    - complex transport pathways between interconnected environmental systems (groundwater-surface water; air-soil-groundwater; etc.).
    - bioaccumulation of PFAS into the food chain from impacted media, such as from contaminated sludges and/or biosolids.
- The multiplicity of sources and pathways (combined with the wide range of potential toxicity values discussed below) can create a sense that everything is equally contaminated and dangerous. Communicators need to help people understand the variability in the degree of contamination and relative risk related to each pathway.
- We are still identifying new PFAS sources (for example, PFAS from compost sites).
- Precursor transformation can affect how a PFAS site will evolve, but this is not well understood.
- Knowledge about uptake by plants and animals is increasing, but it is often difficult to answer questions about specific species.

14.2.3 Toxicological/Epidemiological Information and Risk Assessment

There are challenges and unknowns for toxicological and epidemiological information about PFAS, see Sections 7.1 and 17.2.

- One of the greatest challenges to risk communicators is having to craft messaging in the face of often intense disagreements over the interpretation of available science and the magnitude of uncertainty; we are communicating health risks when the risks are not fully known or characterized.
- There is reliable toxicological information for only a small subset of PFAS.
- A select subset of PFAS has been studied in sufficient detail to support risk assessment and remedial decision-making.
- While human studies may conclude that there is evidence that elevated exposure to PFAS increases the risk of certain health effects, regulatory risk assessment focuses on populations. This means that it is not possible to relate a current health effect in a specific individual to PFAS exposure or to use risk assessment results to predict whether future health effects will occur on an individual basis.
- Although most people have some detectable level of PFAS in their blood serum from consumer products and diet (anthropogenic background), certain populations may have elevated exposure due to localized sources, such as aqueous firefighting foam (AFFF) and industrial discharge, which can contaminate environmental media, particularly drinking water, leading to increased blood serum PFAS to levels that may increase the risk to human health.
- Communities often learn that they have been unknowingly exposed to PFAS for up to several decades prior to the discovery of their presence.
- Community members may want to compare PFAS blood/serum concentrations to PFAS levels in drinking water or other environmental media. A limited number of public-facing tools are available for estimating blood/serum concentrations based on drinking water concentrations, including ATSDR’s Estimator Tool (ATSDR 2022) and Silent Spring Institute’s Digital Exposure Report-Back Interface (DERBI) (Silent Spring Institute 2022).
- Blood serum levels of certain PFAS can remain elevated for many years post-exposure, while levels of other PFAS decrease more rapidly, and currently there is no accepted method to hasten the reduction of PFAS blood levels.
- Individuals may be part of PFAS biomonitoring studies or can obtain their individual blood serum levels on their own. These individuals have access to information for comparison to regional and national reported levels, and thus may be more informed on their personal exposure than the medical practitioner.
- There is a need to provide understandable and informative public health advice to exposed individuals, including woman of childbearing age and pregnant woman who are making decisions about whether to nurse and/or use water known to be contaminated with PFAS to prepare formula (Section 7.1).

14.2.4 Technical

There are technical challenges in the areas of site characterization and treatment technologies, see Section 10 and 12.

- There may be issues in the identification of responsible parties due to the difficulty in distinguishing between low levels of PFAS from use of consumer products (anthropogenic background) and PFAS contamination resulting from discrete sources, such as industrial uses.
- Although a subset of PFAS can be effectively removed by established treatment technologies, effective methods for the remaining compounds are in development.

14.2.5 Analytical Ability

There are technical challenges in laboratory analytical methods and field sampling, see Section 11.

- There are numerous PFAS in existence, yet not all can be measured. Sampling methodologies and analytical procedures to measure PFAS concentrations are still being developed and refined.
- Units used for reporting PFAS concentrations in environmental media and clinical tests are not uniform, and there are differences between blood and serum testing that are not standardized. For environmental professionals, converting and contextualizing these unit differences are routine practice for understanding risks. However, use of varying units may contribute to confusion for general audiences trying to compare and interpret testing results. There are difficulties in clearly and concisely communicating unknowns and limitations of analytical technologies related to the understanding of the extent of PFAS present in the environment, exposure pathways, and magnitude of the potential risk.

14.2.6 Challenges to Risk Communication around Health Risks

When performing risk communication, it is essential to acknowledge that individuals may receive their information from a variety of sources, which may provide conflicting or inconsistent messaging. As presented in Section 7.1, there is a growing body of research pertaining the adverse health impacts of PFAS in humans and laboratory animals. The discussion potential human health risks from PFAS exposure has been taken up in multiple venues, including peer-reviewed scientific studies, news media, and public comments on draft government documents and proposed regulations. The severity and uncertainty of adverse health impacts that may be associated with PFAS and the need for subsequent action has been communicated in an inconsistent manner. Because of the seriousness of potential health effects such as cancer, developmental delays and altered immune system response, as well as the persistence of PFAS in the human body, there is a case for prudence and precautionary mitigation practices to reduce exposures even in the absence of unequivocal human health consequences.

The risk communication challenge around health risks lends itself to a scenario in which stakeholders, including potential responsible parties and federal and state regulatory agencies, are not in consensus on the risk assessment and management strategy. Consistent messaging about uncertainties is essential for risk communication to be successful and to best help those in need. If stakeholders are in debate about the level of risk, then communicate by informing the public that all parties are striving to get the risk evaluation “right” but that there may be a delay in taking action. Communities that may be impacted may request an interim measure, such as an alternate water source, to alleviate concerns with potential exposure. Interim measures coupled with public outreach and community involvement can be a cost-effective risk management strategy in the short term. Public outreach should include measures being taken as well as associated milestones for future actions toward making a more informed risk management decision that utilizes limited resources efficiently, while integrating stakeholder values and community needs.

14.3 Risk Communication Planning and Engagement Tools

Prior to preparing risk communication materials and performing outreach, a project team should develop a risk communication plan to ensure there is a robust risk communication process in place from the outset. A risk communication plan is critical to guide decision makers to determine modes of information transfer as well as stakeholder engagement methods and tools that are appropriate and applicable for identified target stakeholders and site-specific characteristics. As stakeholder concerns and site characteristics are further defined, the communication team will need to continuously revisit the steps of communication planning. The ERIS PFAS Risk Communications Hub is a resource for risk communication information such as state FAQs, case studies and other resources.

In the case of PFAS, many national environmental organizations have made community outreach a major focus. Local grassroots organizations and one, the National PFAS Contamination Coalition (https://pfasproject.net), have led a major effort to inform the public and influence policy. In addition, ATSDR studies (for example, ATSDR 2022) as well as the National Academy of Science (NAS 2022) have included community outreach efforts.

14.3.1 Risk Communication Planning Model

The ITRC Risk Communication Toolkit for Environmental Issues and Concerns presents a risk communication planning model that has eight components, as shown in Figure 14-1. At the center of this model is a step to review and evaluate. This step indicates that communication planning with stakeholders is two-way, ongoing, and continuous, allowing for review of where you are in your outreach efforts and where you may need to go.

This planning model, adapted from the work of NJDEP (2014), facilitates development of project-specific communication plans to be developed at each stakeholder engagement and/or outreach phase of a project. Of note, the NJDEP 2014 document relied on the work of Caron Chess, Billie Jo Hance, and Peter Sandman, Environmental Communication Research Program, Cook College, Rutgers University, as published by the New Jersey Department of Environmental Protection. The model is interactive, which allows for new information to be incorporated into the plan so that the outreach can be modified accordingly. This approach encourages establishing ongoing dialogue between the lead organization and all stakeholders so that the resulting outreach plan reflects the priorities and concerns from all parties. This will help you develop a robust risk communication plan. Section 4 of the Risk Communication Toolkit provides detailed discussion of each of the communication planning model steps. The key aspects of the risk communication planning model are briefly summarized here.

- Issue identification helps you to clearly understand what the situation is in order to develop a responsive and effective risk communication plan.
- Goals are the big picture or ultimate impact that is desired for a project, issue or situation.
- Identification of communities with whom you need to establish a dialogue and those who wish to talk with your organization is important.
- Community assessment is needed to gain a deeper insight into stakeholder concerns and values that facilitate the development of a dialogue. Section 13 addresses stakeholder perspectives for PFAS.
- Messages are the information you want/need to share with audiences about the issue or case, a question that you need them to answer, or both.
- A communication method is the means by which you communicate with your audiences.
- Once you have a clear goal, understand stakeholder concerns, know your message and have selected your method, it is time to lay out the strategy in order to implement the plan.
- Evaluation is the systematic collection of information about activities, characteristics, and outcomes of projects to make judgments about the project, improve effectiveness, or inform decisions about future programming. Many risk communication efforts require an ongoing presence or outreach to stakeholders. A debrief meeting is an opportunity for you to review the results of the evaluation and will identify what follow-up, if any is needed.

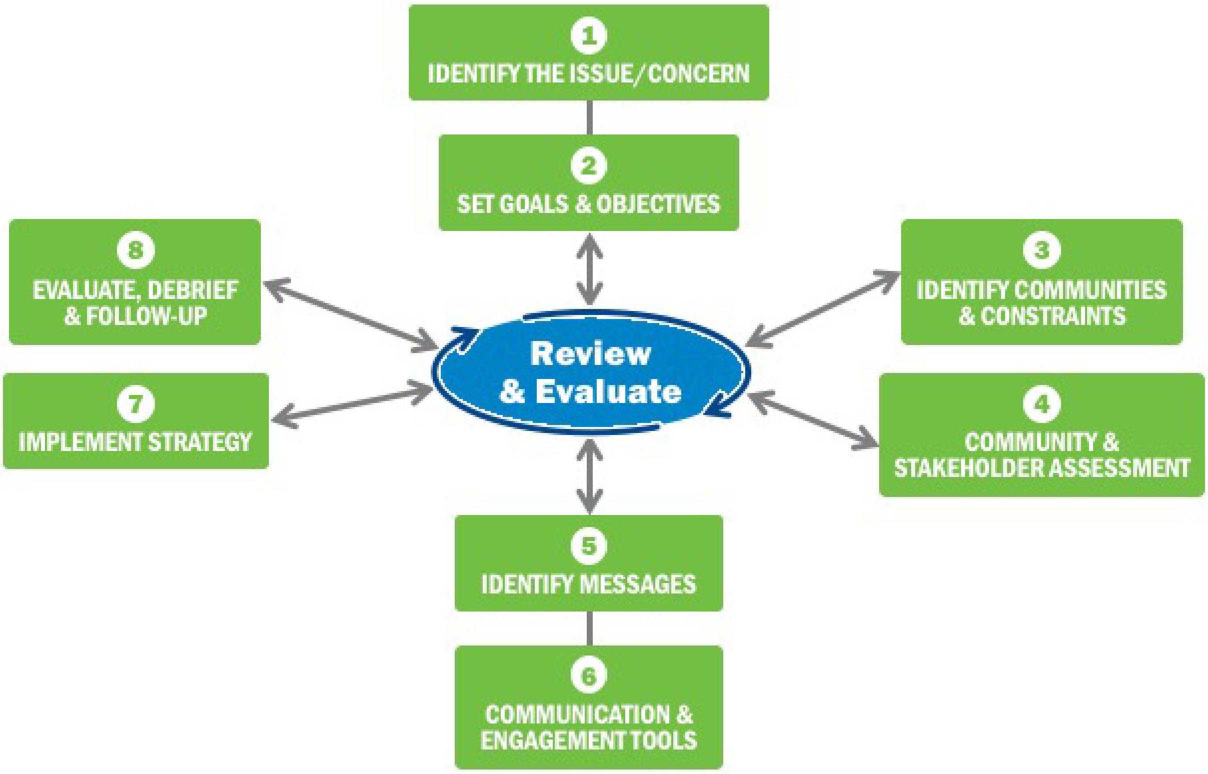


Figure 14-1. Communication plan process diagram.

Source: Modified from NJDEP 2014.

General information about risk communication planning is included in the ITRC Risk Communication Toolkit for Environmental Issues and Concerns document. This toolkit is a good resource for information about risk communication basics and tools. The toolkit can aid decision makers using this process and provide tools to assist with meeting performance metrics at each planning step. In addition, Minnesota Department of Health has developed the *Drinking Water Risk Communication Toolkit*, which can be accessed at https://www.health.state.mn.us/communities/environment/water/toolkit/index.html.

The following subsections are risk communication resources and tools with PFAS examples. The PFAS case studies in Section 15.4 offer examples of community and stakeholder assessment strategies.

14.3.2 PFAS Risk Communication SMART Goals and Objectives

This section includes some examples of SMART (specific, measurable, attainable, relevant, and timely) goals for PFAS. In addition, example messages are included.

Example SMART Goals

Example of Communication of Goals

Issue: The governor established an independent PFAS science advisory panel of national experts to provide guidance to the state on protectiveness of criteria and develop science-based recommendations that will guide the administration and legislature on the best regulatory policy moving forward.

Goal: The PFAS Science Advisory Panel will complete a report within 6 months that will provide a general understanding of human health risks associated with PFAS in the environment. These science-based data will be used to develop a regulatory response that the administration and legislature will take and implement by (date).

Example of Assessing Stakeholder Concerns

Issue: Due to public health concerns, the state agency will conduct a statewide study of PFAS levels in X public water supplies at X schools that operate their own (private) wells by (date.)

Goal: By (date), the environmental agency will develop an inventory and location map of sites where PFAS has been used or disposed; prioritize sites for further investigation based upon the potential to impact drinking water supplies (based upon state groundwater maps, site history, and site ownership); incorporate data into a GIS-based data management system; and develop and implement a plan to sample private and or public water wells to assess potential impacts to drinking water supplies from prioritized sites.

For this example:

- specific: develop an inventory and location map
- measurable: testing
- attainable: implement a plan to sample private and public water supplies
- relevant: testing at prioritized sites will define impact
- timely: by X date

Example of a short-term SMART goal (from the Little Hocking Water Association case study, Section 15.4.1).

- By (date), the community is informed via the municipal website, flyers, and canvassing that bottled water is available as an alternate water source and utilized by 85% of the population.
- After (months), the extent of the impacted water supply is known via well testing and communicated to the community via a public meeting, municipal website, and newsletter.

Example of a long-term SMART goal (from the Little Hocking Water Association case study)

- By (date) and after (months), using a community-first strategy that includes the establishment of a community advisory committee and using multiple methods of communication—media, social media, internet, and meetings—determine whether the study area residents’ blood PFOA levels are elevated and provide actions that 12,000 residents can take to produce a measurable reduction of PFOA blood levels.

14.3.3 Community Identification and Mapping Tools

Due to the persistent and recalcitrant nature of PFAS and its presence in the public drinking water supply, numerous and variant federal, state, private, and public stakeholders can be impacted. Actor mapping is a tool to help guide a communication team to lay out, track, and update stakeholder roles and relationships. During this exercise, practitioners learn who is the most affected by site information and decisions, as well as their level of interest and influence.

The outcome of the tool will assist in identification of unengaged/disinterested stakeholder populations, identify needs for relationship and/or capacity building, develop a site-specific communication team, and target outreach resources toward affected and unengaged/disinterested stakeholder populations. In the context of PFAS, this is of particular importance to identify and address affected groups who may not be participating in preventive and mitigation measures (such as an interim drinking water supply and a fishing ban) and/or at sites in which stakeholder groups are facing conflict resolution.

Simplified **examples** of an actor-linkage matrix and interest-influence matrix are presented, followed by resources to perform complex actor mapping, such as social network analysis. The examples provided are not representative of an existing project; stakeholder roles and relationships vary on a project-specific basis. Different types of mapping approaches can be used based on what visual communication method(s) work best for your organization and stakeholders. The examples provided here (actor-linkage matrix and interest influence matrix) are for demonstration purposes only and are not prescriptive.

Example Context: A PFAS site consisting of a groundwater plume that has impacted drinking water supply wells and has identified contaminants in the local fish population.

Example 1: Actor-Linkage Matrix: A tool that assist practitioners in describing relationships among stakeholders through codes (Reed et al. 2009) (Figure 14-2).

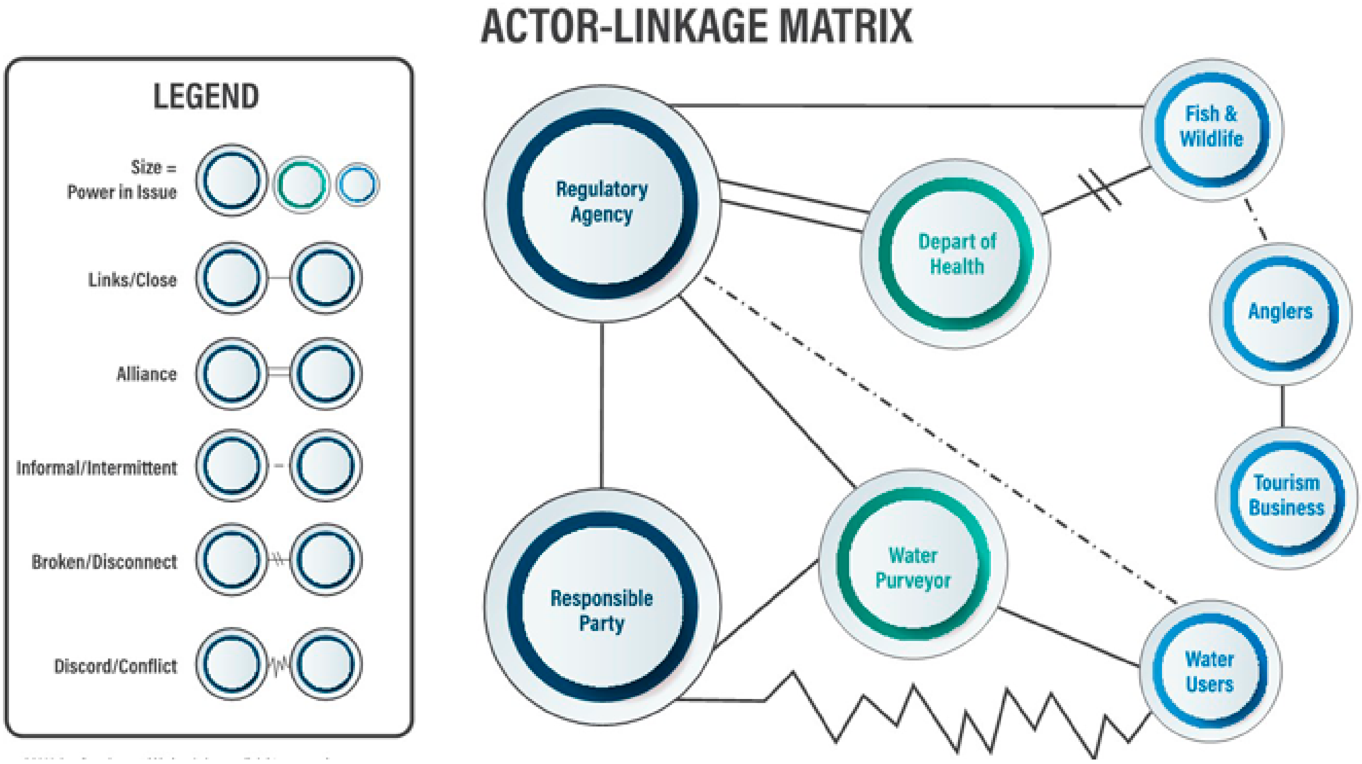


Figure 14-2. Example actor-linkage matrix.

Example 1: Actor-Linkage Matrix Evaluation

- *Identify unengaged stakeholder populations:* potentially anglers and tourism business operators
- *Facilitate relationship/capacity building:* utilize the relationship between the responsible party and water purveyor to restore relationship between the responsible party and water users
- *Identify and develop the communication team:* team consists of a representative for the lead organization and for each regulatory agency, responsible party, water purveyor, and each low-power stakeholder group
- *Target communication strategy resources:* increase information transfer to unengaged stakeholder populations and rebuild intermittent and conflicted relationships with water users in alignment with risk communication strategy SMART goals

The same example is used for the interest-influence matrix.

Example Context: A PFAS site consisting of a groundwater plume that has impacted drinking water supply wells and has identified contaminants in the local fish population.

Example 2: Interest-Influence Matrix: A tool that assist practitioners in identifying the stakes that social actors (stakeholders) have in a cleanup project. Identified stakeholders are placed in a matrix according to their relative interest and influence (Reed et al. 2009) (Figure 14-3).

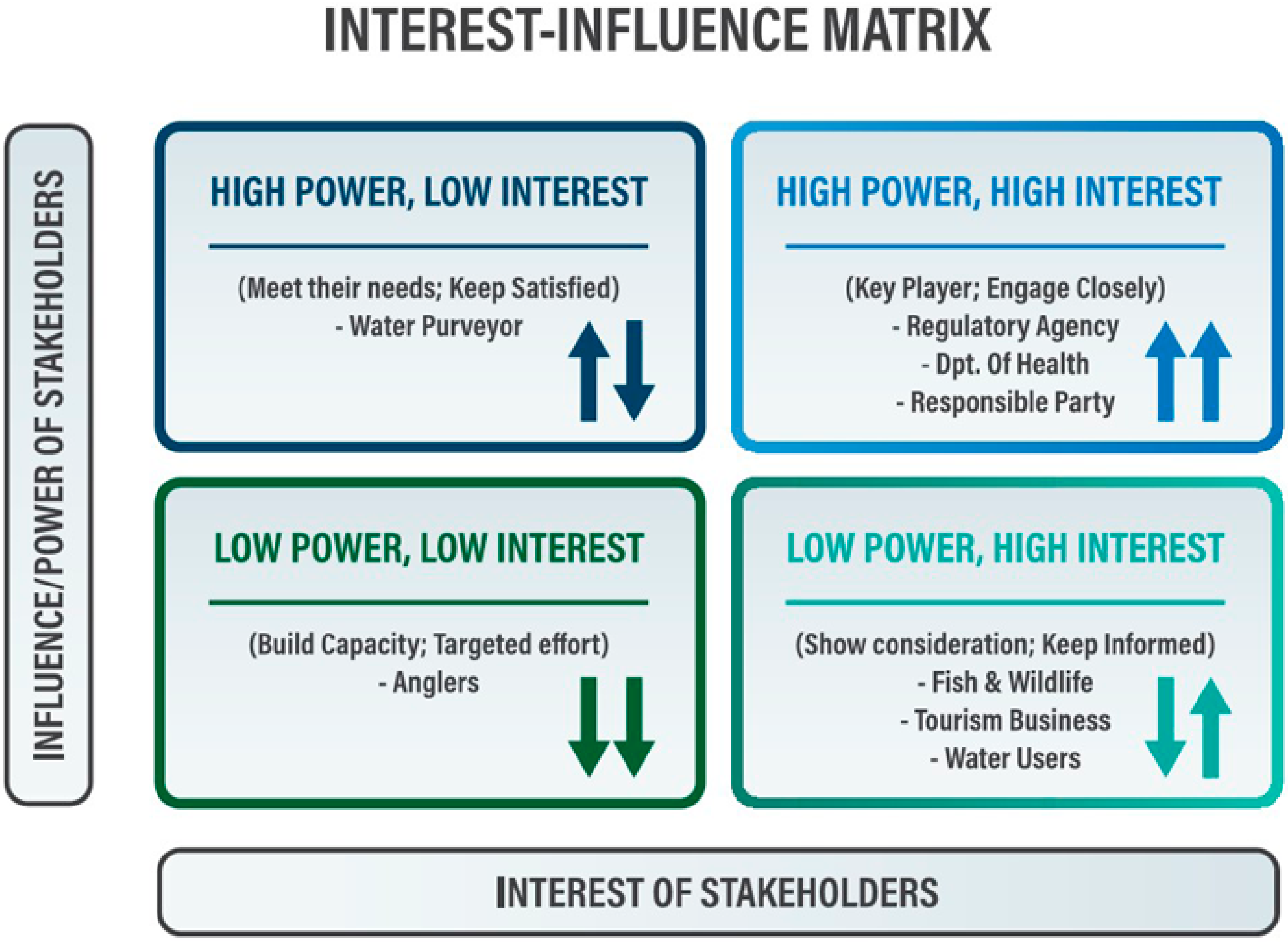


Figure 14-3. Example interest-influence matrix.

Example 2: Interest-Influence Matrix Evaluation

- *Identify unengaged stakeholder populations:* lead organization (for example, state agency or responsible party) (high-power) stakeholders have the role to engage lower power stakeholders who may not be currently engaged or are disengaged
- *Facilitate relationship/capacity building:* utilize high-interest stakeholders to build relationships with lower interest stakeholders, particularly ones with low power (such as the anglers)
- *Identify and develop the communication team:* team comprised of the lead organization and each regulatory agency, responsible party, water purveyor, and a representative of each low power stakeholder group
- *Target communication strategy resources:* increase information transfer to unengaged stakeholder populations and rebuild relationships with low-interest stakeholders in alignment with risk communication strategy SMART goals.

14.3.4 Social Factors Vision Board Tool

Stakeholder risk perception and associated social factors shape individuals’ attitudes toward management of hazards that affect personal safety and public health, and play an important role in supporting legitimacy and compliance with policies and protection measures. Due to the evolving state of the science of PFAS, including appropriate risk management strategies and relevant public policy, the present public attitude toward legitimacy and acceptance of proposed policies and strategies is hindered.

The success of public outreach in terms of exerting a positive influence on community stakeholders and in preventing and mitigating their exposure to a risk is based on site-specific physical, psychological, sociological, and demographic characteristics or “social factors.” Identification of these social factors among individual stakeholder groups can assist practitioners in refining engagement methods and outreach materials to maximize benefits to the community and meet specific needs of the targeted public sector.

A vision board can be used as a medium for stakeholders to rate their level of importance and/or interest on applicable social factors. Identified factors can then be used to further develop SMART goals and key messages, develop public outreach materials, and select engagement methods. The overall objective is to gain deeper insight into stakeholder concerns, values, and preferred communication method to facilitate a two-way street knowledge transfer and capacity building towards a successful risk management strategy. A social factors vision board tool can be used as starting materials for an engagement survey and interview. The target audience for this tool is an established community advisory group or a periodic outreach meeting, focus group, or decision maker stakeholders' group.

The vision boards (see ITRC RC Social Factors Vision Board attachment) developed for this toolkit are focused on a specific topic of concern and associated social factors identified from presentations by public and community stakeholders during the USEPA PFAS community meetings held in 2018.

Note that the vision boards for a specific project are living documents. The statements/questions and social factors should be updated to represent project-specific conditions and stakeholder concerns. Social factors presented on the toolkit vision boards are representative of affected communities' perceptions as opposed to expert opinion based on scientific studies. This toolkit was prepared as an example to provide a starting point for practitioners to understand the present needs and concerns of a PFAS-affected community. In addition, the rating system presented in each board is interchangeable to any social factor topic. More information on using the social vision board are provided in the ITRC Risk Communication Toolkit for Environmental Issues and Concerns document.

14.3.5 PFAS Key Messages

A message is information you want/need to share with communities about the issue or concern, a question that you need them to answer, or both. It is linked to the case specific goal and addresses key points about the issue that were learned through the community assessment. You start with the community and their concerns. Effective messages reflect what your target group needs are as well as what you need to communicate. In the case of emerging contaminants, elements of a message are likely to include: what is known and unknown about a contaminant, acknowledgement of uncertainty; commitment to share new information when it is learned; explanation of how decisions will be made with respect to protecting public health and remediating the problem, etc.

Message mapping is a process for developing your information so that it is concise and includes the information that is critical to convey. The objective is that the message is simple, yet comprehensive enough, and includes the most pertinent information relevant to your issue. A mapped message starts with a question, responds with three key ideas, is no more than twenty-seven words, and takes no longer than nine seconds to deliver. An example of key messages developed for a PFAS site is provided in Table 14-1. Additional resources on key messaging and mapping is provided in the ITRC Risk Communication Toolkit for Environmental Issues and Concerns document.

Table 14-1. Message Mapping Worksheet

Source: (Covello, Minamyer, and Clayton 2007)

Stakeholder: Community member	**Question/Concern/Issue:** What are PFAS and why is the state concerned about them?	
Key Message/Fact 1 PFAS are a family of human-made chemicals in many products used by consumers and industry.	**Key Message/Fact 2:** PFAS are emerging contaminants of concern.	**Key Message/Fact 3:** Some PFAS may adversely impact human health.
Keywords: Supporting Facts 1.1 PFAS are a large group of thousands of manufactured compounds, produced and used for over 60 years. Some PFAS are still in use, some are not.	**Keywords:** Supporting Facts 2.1 PFAS are a contaminant of active scientific research. Scientific knowledge is changing rapidly.	**Keywords:** Supporting Facts 3.1 PFAS can build up in the body (bioaccumulate) and take a long time to leave the body.

Keywords: Supporting Facts 1.2 PFAS have been used in coatings for textiles, paper products, and cookware and to formulate some firefighting foams, and have a range of applications in the aerospace, photographic imaging, semiconductor, automotive, construction, electronics, and aviation industries.	**Keywords:** Supporting Facts 2.2 Laboratory methods may or may not exist to detect all the PFAS contaminants that we know about; methods are developing and evolving with the emerging science.	**Keywords:** Supporting Facts 3.2 Some PFAS, such as PFOA, have been found to impact fetal development and are passed to babies through nursing and bottles.
Keywords: Supporting Facts 1.3 PFAS are found throughout the environment, in people, and in animals and fish.	**Keywords:** Supporting Facts 2.3 Federal and state regulations are changing as the scientific knowledge evolves; this leads to guidance and recommendations that may vary across the country.	**Keywords:** Supporting Facts 3.3 Studies in exposed humans suggest that some PFAS may cause high cholesterol, higher liver enzymes in blood, decreased response to vaccines, decreased birth weight, and testicular and kidney cancer.

A template of the message mapping worksheet is included in Covello, Minamyer and Clayton (2007).

14.3.6 Communication and Engagement Tools

14.3.6.1 Public Outreach

Public health and regulatory agencies have developed several public outreach materials to inform stakeholders about PFAS, from the compounds’ origins and environmental distribution to exposure pathways, associated health effects, and management strategies. Outreach tools include community education classes to inform and support high school teachers, medical professionals, journalists, and municipal water managers. The following provides a summary of available resources for accessing and developing public education materials for PFAS-impacted communities. Although printed public education materials are effective at communicating information, techniques that include face-to-face communication, such as open house meetings, focus groups, and door-to-door canvassing, are often more effective at addressing fears and building trust. Additionally, face-to-face communication provides an opportunity for practitioners to learn from the public and other impacted stakeholders.

The ITRC Risk Communication Toolkit for Environmental Issues and Concerns document includes Guidance for Writing Analytical Results Letter, Guidance for Writing Press Releases.

14.3.6.2 Fact Sheets and Frequently Asked Questions (FAQs)

To achieve effective risk communication, it is essential for public education materials to be presented in a clear and simple manner that is understandable by nonscientists and speaks to a broad audience. Common rules of thumb include writing at a sixth-grade comprehension level, using simple terminology, and providing materials in multiple languages for nonnative speakers. Over the past few years, environmental and public health agencies, nonprofit advisory groups, trade associations, and regulatory agencies have prepared numerous fact sheets and FAQ documents on PFAS-related topics to inform stakeholders, including concerned residents, agricultural and recreational entities, water purveyors, end users, public health professionals, and others. These public education materials developed specifically for PFAS-impacted communities are typically available on the organization’s website.

Fact sheets, FAQs, and other public outreach material should be distributed in multiple modes to maximize audience reach and increase opportunity for engagement. Recommended modes of distribution include mailings, websites, local municipal health departments, public health professional offices, public libraries, and information booths at community events.

The ITRC Risk Communication Toolkit for Environmental Issues and Concerns document includes additional information about FAQs.

- **Compilation of PFAS Fact Sheets, Frequently Asked Questions (FAQs)** and other resources developed by the Association of State and Territorial Health Officials (ASTHO) and the Environmental Council of the States (ECOS) are available:

- https://www.astho.org/PFAS/
- https://www.eristates.org/projects/pfas-risk-communications-hub/

14.3.6.3 Active Centralized Information Repository

Unlike a "passive" repository of site documentation at a central location, an "active" repository refers to a platform that remains up to date on site findings and enables two-way exchange of information among decision makers and the impacted community. A common platform for an active repository is a centralized website that contains a complete compilation of site documentation (among all agencies); frequent updates on site activities, health information and regulatory policy; and a depiction of the CSM (such as a source-exposure pathway graphic and geologic maps). The website should also contain a platform to facilitate stakeholder involvement by providing an opportunity for them to ask questions, submit information, and join a listserv (an application that distributes messages to subscribers on an electronic mailing list).

Examples of centralized websites can be found at the following web links:

- Michigan Department of Environmental Quality, *Michigan PFAS Action Response Team (MPART):* https://www.michigan.gov/pfasresponse/

Michigan agencies representing health, environment, and other branches of state government have joined together to investigate sources and locations of PFAS contamination, to take action to protect people's drinking water, and to keep the public informed as we learn more about this emerging contaminant.

- New Hampshire Department of Environmental Services (NHDES), *NH PFAS Investigation*: https://www4.des.state.nh.us/nh-pfas-investigation/

NHDES maintains a website to update interested parties on NHDES's investigation into the presence of PFAS in New Hampshire. The website includes a map that shows PFOA and PFOS data from water samples collected around the state.

- Vermont Department of Environmental Conservation (VDEC), *Vermont PFOA Contamination Response*: https://dec.vermont.gov/pfas/pfoa

Numerous Vermont agencies, including VDEC, Department of Health (VDH), Emergency Management, Agency of Agriculture, and Agency of Education have joined together to investigate and address PFAS contamination in Vermont. VDEC and VDH have created and maintained web pages to push information out to the public as it becomes available to keep the public informed of the PFAS issue.

Not all stakeholders have access to the internet, and depending upon the seriousness of the site's situation, it may be appropriate to hold regular meetings and/or office hours to provide more than one mode for stakeholders to obtain information and engage with decision makers.

14.3.6.4 Community Education

Individual stakeholder groups and individuals themselves process information in a variety of modes and media. An effective risk communication strategy takes this factor into consideration and encompasses multiple forms of outreach. In addition to informative materials, such as fact sheets, stakeholder meetings and interactive sessions (such as poster presentations, question and answer sessions) can be held to involve individuals in the learning and understanding process. Prior to selection of a method, an audience assessment should be conducted to determine how a community communicates and to learn what tool is the most effective to use.

Community Education Example—Bennington College Community Education Strategy, Vermont

In 2016, PFAS were discovered in the public water system of Hoosick Falls, New York, and in hundreds of private residential wells in Petersburgh, NY, and North Bennington, Vermont. In response to this nearby problem, Bennington College asked how the scientific resources of a college or university might become a civic resource in times of environmental uncertainty. After some discussion about how to maintain the scientific and educational integrity of the college while also being a good neighbor to impacted communities, Bennington College decided to open the doors of its science classrooms to the problem of PFAS contamination. This was done primarily in two ways: (1) a new introductory class on PFOA was offered to local communities free of charge, and (2) students in more advanced science classes in chemistry and geology worked to produce independent data on PFAS contamination in the region. More information about both of these strategies is below.

Many residents impacted by PFAS voiced a desire to learn about the science of the problem even as there was a recognition that much of that science was currently quite difficult for residents to grasp. Indeed, many of the risks and ramifications of PFAS contamination are currently published in daunting regulatory reports and peer-reviewed research articles (often behind paywalls). Addressing these concerns, Bennington College designed a new class to review the chemical properties, environmental pathways, and policy concerns of PFOA, entitled “Understanding PFOA.” This class also taught residents how to collect water samples for PFAS analysis at a commercial lab and how to interpret laboratory results from PFAS analysis. Bennington College has offered this class every spring to local residents since 2016, free of charge. A number of local teachers, journalists, nurses, elected officials, parents, and students enrolled, and the class has become a vehicle for the community to get up to speed on the science of PFAS so they can engage the issue more productively.

Bennington College also put together faculty-led research teams to produce independent data on PFAS contamination in conversation with community questions. Bennington College realized that impacted communities often had interesting questions about PFAS that fell outside of the urgent protocols of state agencies, which rightfully focused on safeguarding public health. These community questions, however, provided useful pathways to educate residents about the problem and to encourage local participation in research into PFAS contamination. Working with residents of Hoosick Falls, Petersburgh, and North Bennington, the college helped investigate a number of community concerns, such as:

- “Is there any PFOA in my maple syrup?”
    - Bennington College tapped two maple trees in the spring and analyzed the sap, finding 8.8 parts per trillion (ppt) of PFOA in the sap of a maple tree about 1,000 feet from a plastics plant and 2.3 ppt of PFOA in the sap of a maple tree about a mile from the plant.
- “My well had high levels of PFOA but now I have a filtration system in my basement. If my well was contaminated for years, I wonder if there might be any residual PFOA in my water pipes. Could any built-up PFOA still be contaminating the water coming out of my kitchen faucet?”
    - Bennington College analyzed water from the kitchen faucet from three homes with high levels of PFOA in their well and a point of entry treatment filtration system (Hoosick Falls house, 2,100 ppt of PFOA in well; Petersburgh house, 1,800 ppt of PFOA in well; North Bennington house, 3,000 ppt of PFOA in well). In all three homes, PFAS were nondetectable in water from the kitchen sink.
- “When the state tested my well, they found PFOA levels just below the health guidance level and thus we did not get a filtration system. How stable are detected levels of PFOA in the groundwater?”
    - Bennington College reviewed data from over 200 residential wells that had been sampled and analyzed for PFOA at least twice in one year. They found an average variation of 24% in individual wells. PFOA levels increased in about half of the wells and decreased in about half the wells. This increase and decrease did not have an obvious spatial pattern (for example, a plume moving in one direction) but appeared to be fairly randomly scattered across the sampling area.

More information about Bennington College’s ongoing engagement with PFAS can be found at www.bennington.edu/pfoa.

Updated September 2023.

15 Case Studies

Currently the PFAS team has identified case studies supporting the following sections:

- Section 10 Site Characterization
- Section 12 Treatment Technologies
- Section 9 Risk Assessment
- Section 14 Risk Communication
- Section 16 Surface Water Quality

15.1 Site Characterization Case Studies

15.1.1 Data Visualization at an AFFF Release Site

McGuire et al. (2014) and McGuire (2013) presented a detailed characterization of a subset of PFAS soil and groundwater concentrations, focused on PFAAs in the vicinity of a former unlined burn pit where fire training activities were conducted up to 1990. Data presented in McGuire et al. (2014) were used for this visualization example. For brevity, this example shows relative concentration trends between shallow and deep soil samples collected at six borings where total PFAA concentrations exceeded 5,000 ug/Kg in shallow soil. The inset map in the top left of Figure 15-1 shows the former burn pit location, as well as the locations of these six borings (S-2, S-4, S-5, S-6, S-7, and S-10). Shallow soil samples were collected at a depth of approximately 2 ft below ground surface (ft bgs) (0.61 m), and the deep soil samples were collected at the water table, which is approximately 15–20 ft bgs (4.6–6.1 m) on average.

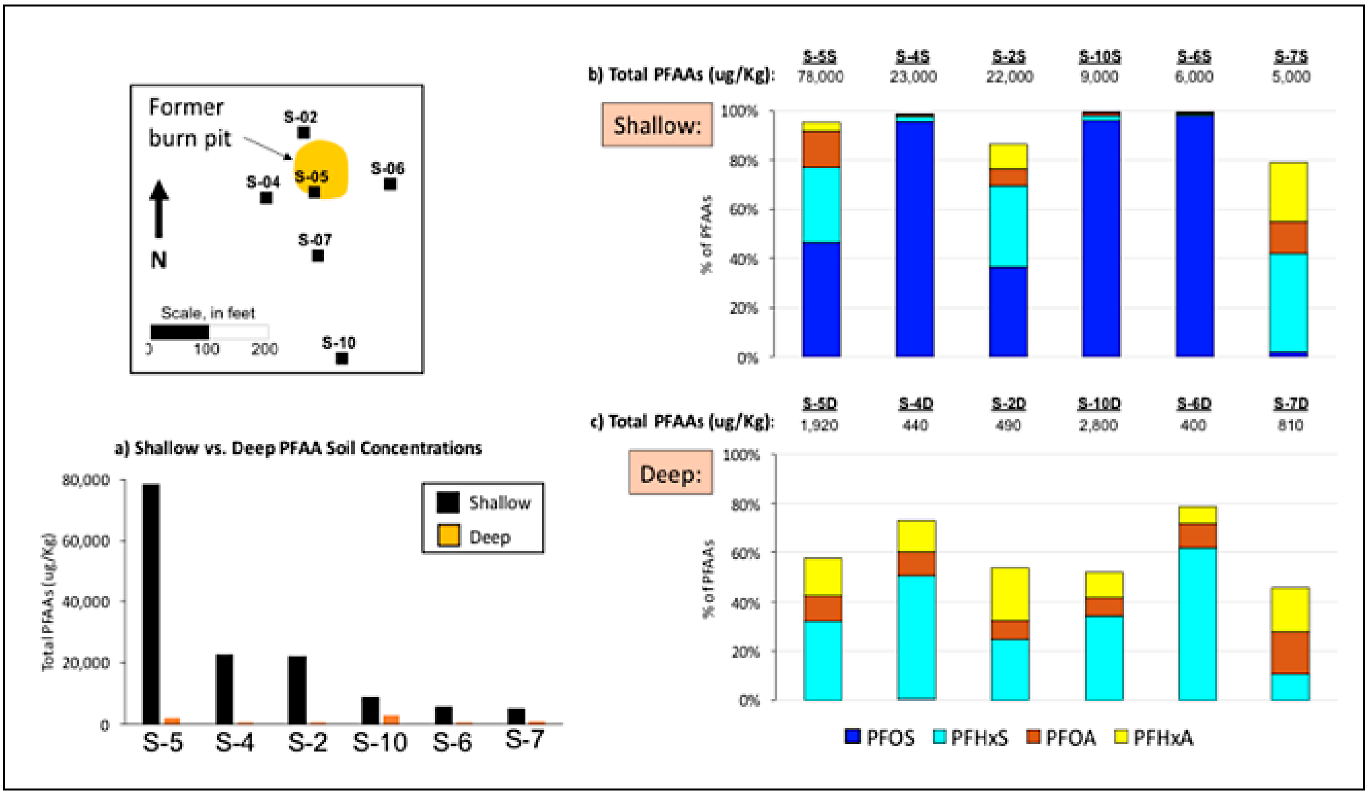


Figure 15-1. Comparison of shallow and deep soil samples at an AFFF release site.
Source: G. Carey, Porewater Solutions. Used with permission.

The bar chart in Figure 15-1a compares concentrations of shallow and deep soil concentrations for total PFAAs at these six boreholes and clearly demonstrates that shallow PFAA soil concentrations are much higher than deeper soil concentrations at the water table. This figure indicates that there is likely attenuation that limits vertical migration of PFAAs. McGuire (2013) attributed this to the high clay content of vadose zone soils, and high VOCs and TOC in this area, which may enhance retardation.

A different type of bar chart is shown in Figure 15-1b to illustrate the composition of the main PFAA constituents in shallow soil samples (PFHxS, PFOS, PFHxA, PFOA). Review of Figure 15-1b reveals the following trends:

- In three of the six boring locations, PFOS is greater than 95% of total PFAA concentrations in shallow soil.
- In the other three borings, PFOS is less than 50% of total PFAAs. These borings have higher relative concentrations of PFHxS, PFHxA, and PFOA.
- PFHxS, PFOS, PFHxA, and PFOA combined represent at least 80% of total PFAA concentrations in shallow soil.

The difference in PFOS composition shown in Figure 15-1b suggests that some borings were drilled in an area that was influenced by a mixture of different AFFF products, whereas other borings with a high proportion of PFOS may be influenced primarily by AFFF produced using electrochemical fluorination.

Figure 15-1c shows the same type of bar chart with relative percent of total PFAA concentrations for the deeper soil samples collected at the water table. Comparison of Figures 15-1b and 15-1c indicates that there is a clear difference in PFAA composition between the shallow and deep soil samples. PFOS is very low in terms of relative concentrations in deep soil samples, compared to the shallow soil samples where PFOS makes up a higher proportion of the total PFAA concentration. This may be due to enhanced retardation of PFOS in the vadose zone relative to the other compounds (PFHxS, PFHxA, and PFOA), which is consistent with the relative site-specific K_{oc} values determined by McGuire et al. (2014). In addition, Figure 15-1c shows that these four compounds typically represent only around 50% of total PFAA concentrations in the deep samples, which suggests that shorter chain compounds are more prevalent at the water table and in underlying groundwater, most likely due to precursor transformations.

Radial diagrams may also be used as visual aids to illustrate spatial and/or temporal trends for individual PFAS constituents or total concentrations for various PFAS groups. As an example, Figure 15-2 presents a radial diagram map showing trends for various PFSAs (PFOS, PFHxS, PFBS) as well as perfluorohexane sulfonamide FHxSA, which is a precursor to PFHxS. The radial diagram legend in the top right portion of Figure 15-2 shows that the four axes are arranged in order of FHxSA, PFOS, PFHxS, and PFBS. There are two data series shown on the radial diagram legend: (1) the blue-filled data series, which represents PFAS constituent concentrations at monitoring well location; and (2) a darker blue outline that represents maximum source concentrations at well GW13, which is situated directly adjacent to the former burn pit area. This latter data series is a reference and is the same at all monitoring well radial diagrams. Including this reference data series makes it easier to visualize changes in concentrations throughout the plume. The radial diagram legend also shows how symbols may be plotted to represent where constituents were not detected in a groundwater sample. Another option for radial diagram symbols is to indicate where concentrations are above groundwater cleanup criteria at each well location (not shown). The compound axes are logarithmic in this example, to allow for visualization of order of magnitude concentrations between wells, or between compounds at any one well location.

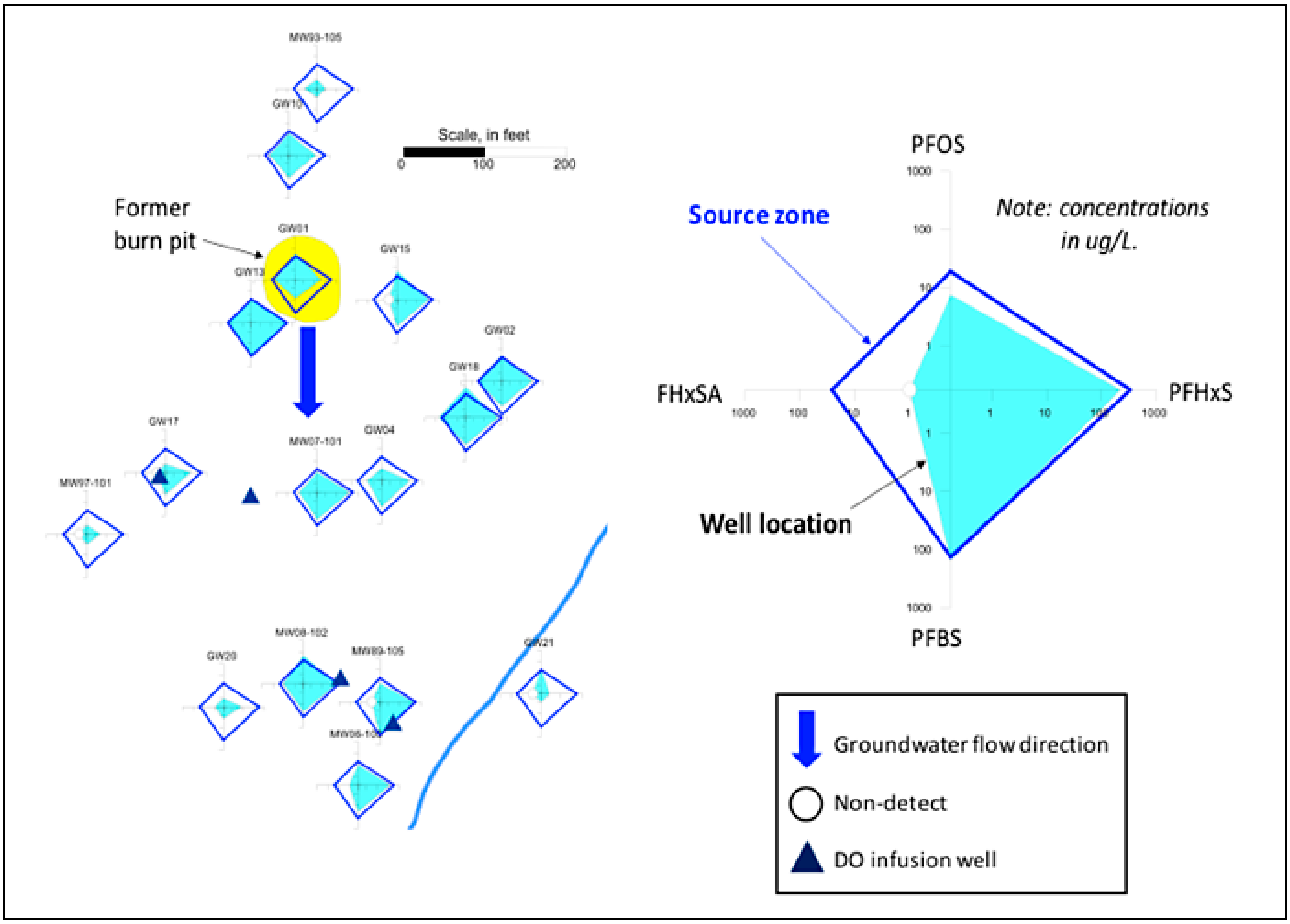


Figure 15-2. Radial diagrams illustrating PFSA trends at an AFFF release site.

Source: G. Carey, Porewater Solutions. Used with permission.

Groundwater flow in this area is generally to the south/southeast. The main radial diagram map shown in Figure 15-2 facilitates an analysis of how concentrations for these four constituents vary along the groundwater flow path downgradient from the former burn pit area, and how concentrations vary across the width of the plume. For example, the radial diagram shown at GW01, which is located inside the footprint of the former burn pit, indicates that concentrations of the longer chain compounds (FHxSA and PFOS) are similar to those in the nearby well at GW13, whereas PFHxS and PFBS are about an order of magnitude lower at GW01 then GW13. The radial diagrams also clearly show that groundwater downgradient of the DO infusion wells (triangle symbols) has low to non-detect FHxSA, indicating that aerobic transformation of this precursor has occurred downgradient of these infusion wells (Section 10.4.4).

Although not shown with this case study, radial diagrams are also helpful for visualizing redox indicator trends, to confirm whether redox conditions are favorable for the transformation of precursors to PFAAs. Examples of a modified radial diagram method used for redox zone delineation are presented in Carey et al. (1999) and Carey et al. (2003).

15.1.2 Application of Radial Diagrams

Figure 15-3 presents another type of application of radial diagrams for visualizing certain PFAS trends, in this case for an aquifer contaminated with PFAS from several fire training areas in the vicinity of Uppsala, Sweden. The blue outlines shown in Figure 15-3 represent the boundaries of eskers (deposits formed by streams flowing beneath a glacier), which essentially act to channel groundwater flow in the aquifer. The legend shown on Figure 15-3 indicates that the four axes of the radial diagram now represent concentrations of 6:2 FTS (which dominates the other FTSs), total PFCAs, total PFSAs, and total concentrations of other chemical-specific precursors. Symbols are shown to represent non-detects at each well location. Groundwater flow in the main aquifer channel is from northwest to southeast (parallel to the river channel) and is to the west in the inset box shown in the bottom center of Figure 15-3.

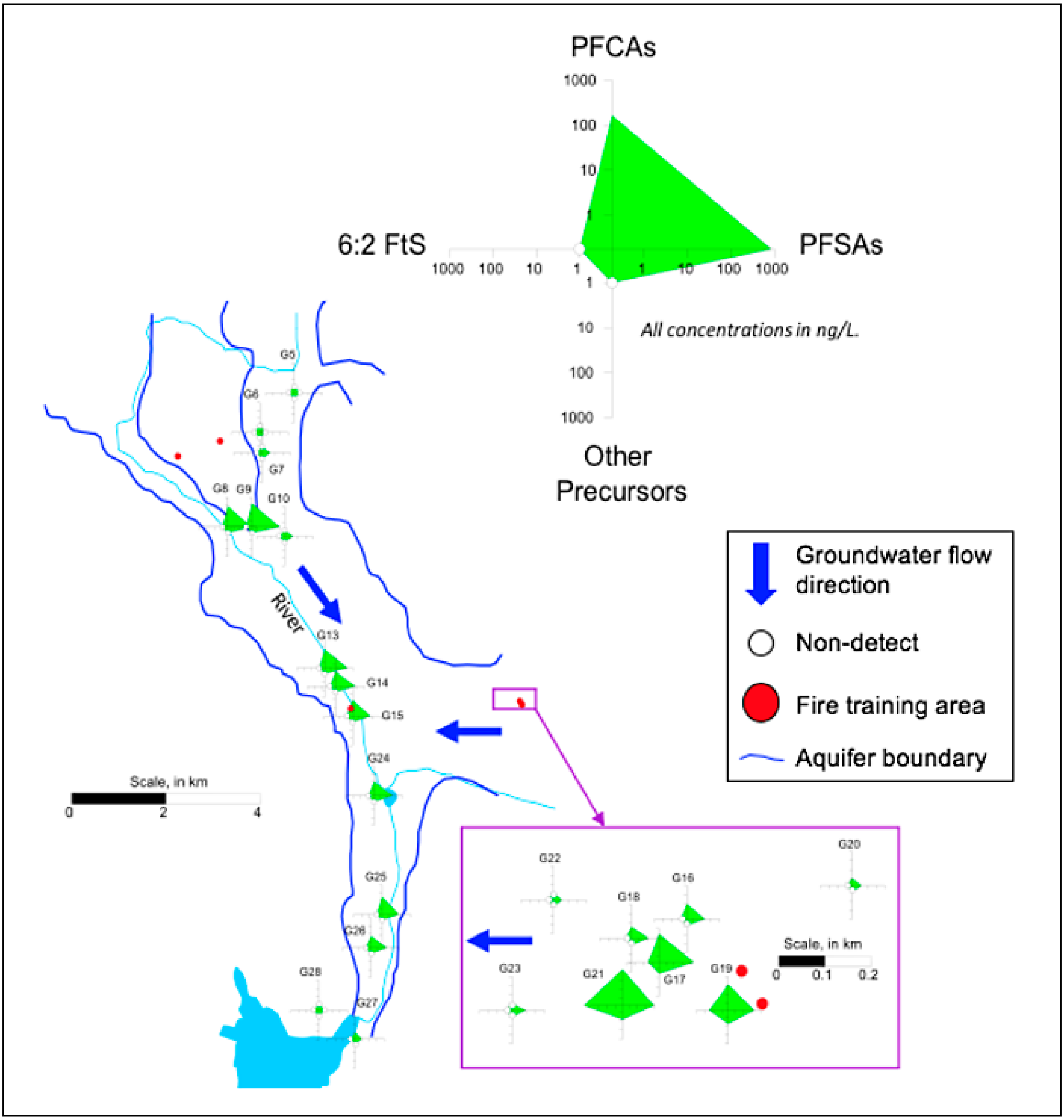


Figure 15-3. PFAS composition in groundwater.

Source: G. Carey, Porewater Solutions. Used with permission.

Examples of trends that are evident based on the radial diagram map (Figure 15-3) include:

- All chemical-specific precursors are nondetect in the main aquifer channel, indicating that precursors were effectively attenuated closer to the fire training areas.
- PFSA and PFCA concentrations appear to be declining along the main flow channel (for example, downgradient of G8 and G9.
- Concentrations of precursors in the vicinity of the fire training areas shown in the inset map are much higher than in the main groundwater flow channel. This indicates that precursors may be attenuating prior to reaching the main flow channel in this area, due to sorption, biotransformation, and/or possibly discharge to the nearby creek.
- The combination of elevated PFCAs and PFSAs, as well as high 6:2 FtS near at least two of the fire training areas, indicates that AFFFs produced using telomerization were used at one point at some of these fire training areas.

15.1.3 Application of Environmental Sequence Stratigraphy (ESS)

Due to the high mobility and persistence of PFAS, groundwater plumes may extend to greater distances than those observed for conventional contaminants such as hydrocarbons and chlorinated solvents. Consequently, PFAS plumes may be more susceptible to unusual groundwater plume flow patterns. For example, site geology may cause groundwater plumes to diverge from directions predicted based on evaluation of a groundwater potentiometric surface (hydraulic gradient). Furthermore, longer groundwater plumes experienced by PFAS may result in groundwater/surface-water interaction to a greater extent. The case study presents an example where environmental sequence stratigraphy (ESS) is used to update a conceptual site model (CSM) for a PFAS-impacted site.

ESS (USEPA 2017) is a data analysis technique designed to improve CSMs through enhanced understanding of interaction between site geology, groundwater flow patterns, and preferential contaminant transport pathways. ESS provides a framework for interpretation of data generated via high-resolution site characterization (HRSC), existing subsurface data, such as geologic boring logs, and (potentially) geophysical data. The data evaluation focuses on site depositional/erosion history to identify geologic sequences and patterns (geologic heterogeneity and anisotropy in hydraulic conductivity) that explain contaminant migration pathways. ESS is useful to identify patterns in sedimentary deposits (consolidated or unconsolidated) comprising clays, silts, sands, and gravels. ESS techniques are designed for sedimentary deposits and are not applicable to metamorphic/crystalline rock or glacial till; however, adjusted ESS techniques can also be applied to glacial outwash deposits, which have similar characteristics to nonglacial sedimentary deposits.

This case study describes a site where ESS predicted a groundwater plume that did not follow the direction expected via simple hydraulic gradient analysis.

15.1.3.1 Sequence Stratigraphy

Sequence stratigraphy involves the study of geologic heterogeneity in sedimentary deposits in the context of their depositional environments and is applicable to sites underlain by sedimentary aquifers (for example, intermixed gravels, sands, silts, and clays). Subtle geologic heterogeneities can have significant effects on groundwater and contaminant transport. The ESS framework is designed to evaluate and incorporate these heterogeneities into a CSM to improve understanding of contaminant fate and transport. ESS techniques involve three-dimensional evaluation of geologic data, with an experienced geologist looking for detailed patterns and trends in the depositional framework (for example, lateral and/or vertical continuity of geologic strata).

ESS implementation generally involves a three-step process. The first step involves review and understanding of the regional geology and depositional environment. The second step involves a detailed review of existing lithology data, to assess both vertical and horizontal grain-size sedimentary patterns. Additional information may also be incorporated at this step, such as geophysical data and/or manmade site features (for example, drainage pathways). The third step involves development of a CSM integrating the detailed geologic data collected during the preceding steps to develop a hydrostratigraphic understanding of what controls migration of groundwater and contaminants. During this third step, three-dimensional data-modeling tools may be used to interpret the lateral continuity of subsurface strata, identify trends and/or lithologic sequences, and integrate geology and geochemical data sets.

This method can identify preferential groundwater and contaminant flow pathways associated with the geology and hydrogeology that may not be apparent in conventional/engineering-focused investigations, and may not necessarily follow the general groundwater gradient. Furthermore, ESS techniques can be useful to map and predict contaminant mass transport, identify data gaps, and identify target locations for focused investigation and/or remediation.

15.1.3.2 Site Background

An updated CSM (Trihydro 2019) was prepared for Ellsworth Air Force Base, where previous training and incident response involving aqueous film-forming foam (AFFF) resulted in groundwater impacted by PFAS as documented in a PFAS site inspection report of aqueous film forming foam areas (Aerostar 2019). Historical site investigations were typically focused on specific operable units (OUs) in a piecemeal fashion. As a result, geologic and hydrogeologic connections between some OUs were not apparent. Furthermore, previous investigations focused on contaminants of concern such as trichloroethene (TCE).

A detailed evaluation of regional and site geology was conducted in accordance with the ESS framework and is summarized herein. Briefly, regional geology consists of confined and unconfined aquifers. The shallow, unconfined aquifer comprises unconsolidated sediments (terrace alluvium) overlying the Pierre Shale formation, which covers a large segment of the plains surrounding the Black Hills and is reported to be up to 860 feet thick at the site. The Pierre Shale is a low-permeability formation that functions as a barrier to vertical groundwater flow, and as a confining unit to deeper aquifers. Deeper, confined aquifers exist at depth beneath the Pierre Shale. The Pierre Shale is considered the bedrock surface at the site and is encountered between 0 and 40 feet below ground surface.

The CSM focused on the shallow aquifer, defined as a terrace alluvium, which includes a combination of paleochannel deposits, modern channel deposits, and undifferentiated sediments (see geologic cross-section shown in Figure 15-4). The undifferentiated sediments are poorly graded deposits associated with floodplains, wind, or other weathering, which are generally more fine-grained and lower permeability than the channel deposits. The paleochannel deposits consist of sand and gravel, deposited by ancient surface-water streams, with characteristics including high permeability and fining-upwards sequences. The paleochannel deposits underlying Ellsworth AFB provide preferred pathways for groundwater and contaminants with unpredictable orientations that are not discernable from the direction of modern drainages.

For the updated CSM, the site depositional history was evaluated, along with historical geologic and hydrogeologic data sets. The project involved “synthesizing decades of lithology data, from over 1,100 boreholes [within a site area of approximately 4,800 acres] with varying geologic interpretation” (Trihydro 2021). Site depositional history was evaluated and lithology logs were compiled and integrated with manmade infrastructure features to map out fine-scale geologic features and identify trends and pathways that affect contaminant migration. The large number of existing boreholes provided a rich data set for ESS evaluation, and a multimonth effort was required to review the existing logs and convert the logs into digital format, As part of the ESS evaluation, the project team “looked at fine scale stratigraphic patterns in the contaminant transport pathways to predict where additional remedial solutions should be located” (Trihydro 2021). One of the questions posed midproject was to figure out how the shallow groundwater, outside of the base boundary, had become impacted by PFOA/PFAS. The area was approximately 0.5 miles from any known release or storage area.

15.1.3.3 Results

The CSM developed for Ellsworth AFB used ESS techniques to show how geologic heterogeneity and anisotropy, resulting from site depositional history, caused multiple PFAS groundwater plumes to diverge from the direction predicted using simple potentiometric surface maps. The ESS evaluation identified several course-grained channel structures throughout the site. “More specifically, the CSM showed how buried paleochannel structures and a subtle weathered bedrock surface controlled contaminant migration pathways” (Trihydro 2021). In addition, subsurface stormwater structures were identified as high-permeability conduits, potentially providing secondary migration pathways for contaminants off site.
As illustrated in Figure 15-5, the groundwater plume (the TCE plume is shown in yellow) diverges from the prevailing groundwater flow direction (blue arrows) after encountering a course-grained paleochannel (shown in dark pink). The TCE plume is illustrated on Figure 15-5 due to the extensive historical data set for TCE that is amenable to detailed plume mapping, better than would be the case for PFAS; the PFAS data set remains relatively limited (but growing) at the site. Detailed geologic cross-sections generated through the ESS evaluation (Figure 15-4) provide further insights into the structure of the paleochannels that influence the plume behavior. “Through ESS techniques, portions of previously unidentified plumes were found” (Trihydro 2021), and subsequent PFAS site characterization and/or remediation activities will rely on the new understanding moving forward to provide a more accurate remedial strategy.

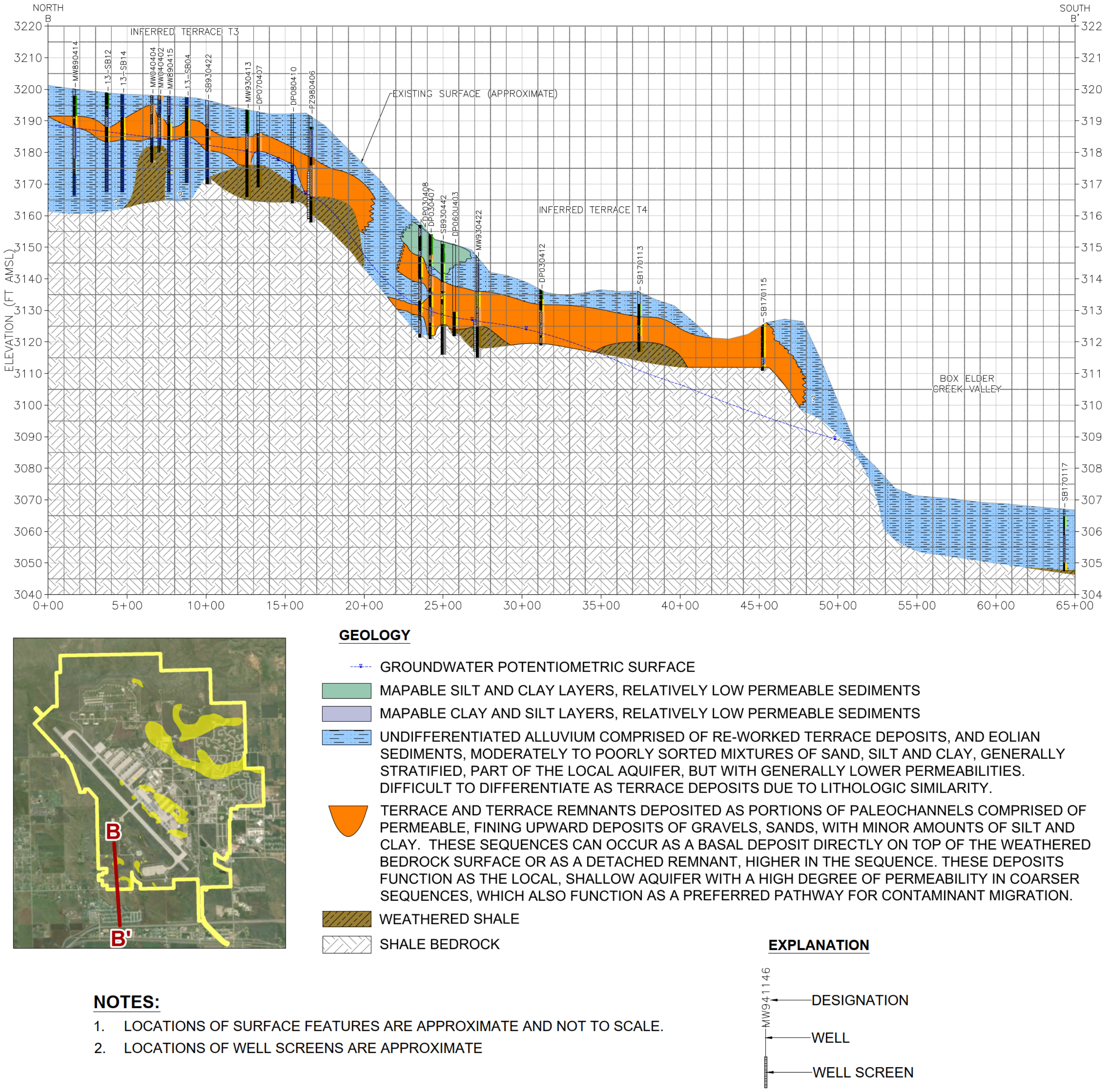


Figure 15-4. Geologic cross-section generated from ESS evaluation (Trihydro 2019).

Source: M. Olson, Trihydro. Used with permission.

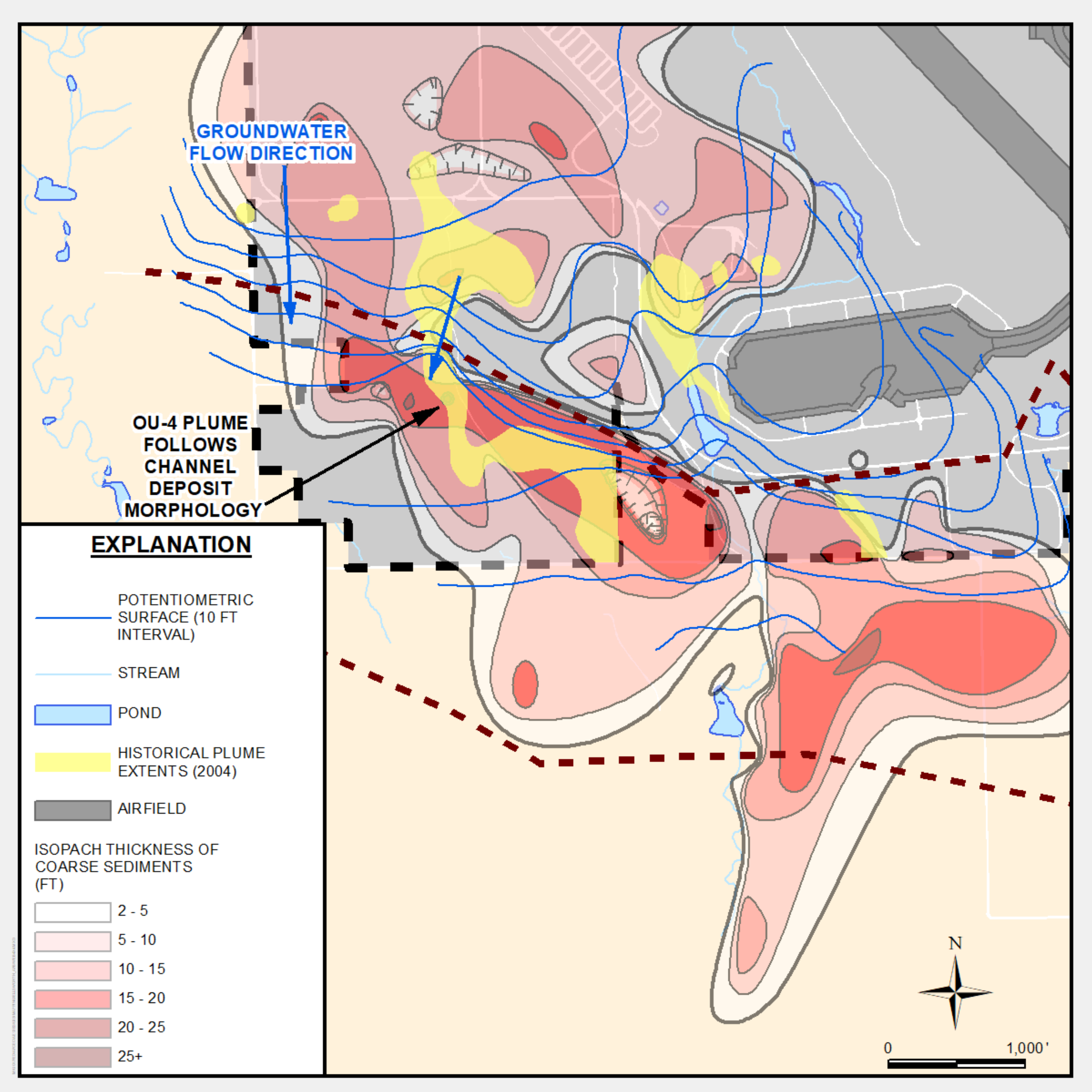


Figure 15-5. Excerpt from TCE plume map (Trihydro 2019).
Source: M. Olson, Trihydro. Used with permission.

15.2 Treatment Case Studies

Several well-developed technology case studies are presented in the following sections. Additional information on other water treatment case studies is summarized in Table 15-1 provided as a separate Excel file.

15.2.1 Granular Activated Carbon (GAC)

Case Study: Granular Activated Carbon System—Oakdale, Minnesota (Contributed by Virginia Yingling, Minnesota Department of Health, used with permission)

Background

Oakdale is a suburban community located east of St. Paul, Minnesota, with a population of approximately 28,000. Prior to state or federal laws regulating such waste disposal, industrial wastes from a PFAS manufacturer were disposed of in a privately operated 55-acre unlined dumpsite (Oakdale Disposal Site, 1940–1960) and in the Washington County Landfill, a permitted 40-acre unlined municipal landfill in Lake Elmo, Minnesota (1969–1975). In 2005, PFAS were detected in six of the eight operating Oakdale city drinking water supply wells.

Eight PFAS have been detected in groundwater associated with these sites, with PFBA, PFHxS, PFOA, and PFOS being present at the highest concentrations. PFAS have also contaminated a stream that drains the wetlands that comprise part of the Oakdale Disposal Site and PFAS re-infiltration has contributed to groundwater contamination in areas not immediately downgradient of the waste disposal sites. Both sites underwent remedial activities in the 1980 to address industrial solvents and in 2009–2011 to address PFAS. These actions included soil and waste excavation with on- and off-site encapsulation, and groundwater pump and treat (GAC) for hydraulic containment.

The regional groundwater flow direction at both sites is to the south-southwest toward the Mississippi River, approximately 8 miles away. The primary source for PFAS impacts to groundwater appears to be the Oakdale Disposal Site, but the Washington County Landfill may have contributed to the contamination in the easternmost city wells.

Water Characteristics

The maximum concentrations detected to date in the city wells are shown in Table 15-2 along with the relevant Minnesota health-based guidance values for PFAS in drinking water.

Table 15-2. Maximum concentrations of PFAS in drinking water from Oakdale city wells.

Chemical	Maximum Concentration Detected in Any Oakdale City Well (µg/L)	Minnesota Department of Health’s Health-Based Guidance Value (µg/L)
PFBA	2.15	7
PFBS	0.136	3 (acute), 2 (chronic, subchronic)
PFPeA	0.176	None established
PFHxA	0.382	None established
PFHxS	0.142	0.047
PFOA	0.871	0.035
PFOS	1.38	0.015
NOTE: All concentrations reported as of August 2019 and guidance values reported are as of December 2019.		

The Minnesota Pollution Control Agency (MPCA), Minnesota Department of Health (MDH), City of Oakdale, and the chemical manufacturer agreed to address the situation by constructing a GAC treatment plant to treat the water from the two most highly contaminated wells. In addition, the city shut off one well and drilled a replacement well north of the contaminated area. Other wells with PFAS detections are used seasonally and to maintain pressure throughout the distribution system, but the pumping schedule is managed to ensure PFAS remain below MDH guidance values in the water delivered to the community. This includes meeting the MDH’s Health Risk Index, which is a toxic equivalency quotient (TEQ)-like assessment of the additive toxicity of multiple PFAS.

Treatment Technology Design Details

The GAC treatment facility (Figure 15-6) began operations in October 2006. It consists of ten filter vessels (each containing 20,000 lbs. of GAC) set up in five parallel lead-lag pairs (shown below) housed in a 7,000 ft^2 facility. The system treats 2,500 gallons per minute with a minimum empty bed contact time (EBCT) of 10 minutes per vessel. The water is combined back into one stream, chlorinated and fluoridated to meet state and federal standards, and then piped to the distribution system.

Figure 15-6. GAC treatment system, Oakdale, MN.
Source: Courtesy of the Minnesota Department of Health.

System Performance

The city and MDH monitor the PFAS concentrations in the influent, lead vessel effluent (that is, between vessels), and post–treatment facility effluent (Figures 15-7 and 15-8). Monitoring currently occurs quarterly for the first three quarters following GAC change-out and monthly in the final quarter prior to change-out.

The GAC is changed out approximately every 12 months to prevent breakthrough of any PFAS above MDH guidance values. GAC change-out may involve a complete replacement of all GAC or just the lead vessel GAC and change of flow to make the former lag vessel the new lead vessel. This will depend on the effluent concentrations at the time of change-out. Initial removal rates are 100% (below analytical limit of detection) for all seven PFAS analyzed (PFBA, PFPeA, PFHxA, PFOA, PFBS, PFHxS, PFOS).

Breakthrough order follows the expected sequence of shorter chain and PFCAs preceding longer chain and PFSAs. PFBA breakthrough of the full system typically occurs within 2 months after a complete GAC replacement, but because the influent PFBA does not exceed its health-based guidance value of 7 µg/L, this does not pose a health risk and does not trigger any response actions. Interestingly, PFBA effluent concentrations eventually exceed influent concentrations, presumably due to PFBA desorbing in the presence of more readily sorbed, longer chain PFAS. As shown in the graphs below, PFOS has broken through the full system only once (2012; max effluent concentration = 0.019 µg/L) and PFOA has broken through only four times (2010, 2012, 2015, 2018; max effluent concentration = 0.086 µg/L). At no time did any PFAS exceed the then-current health-based guidance values.

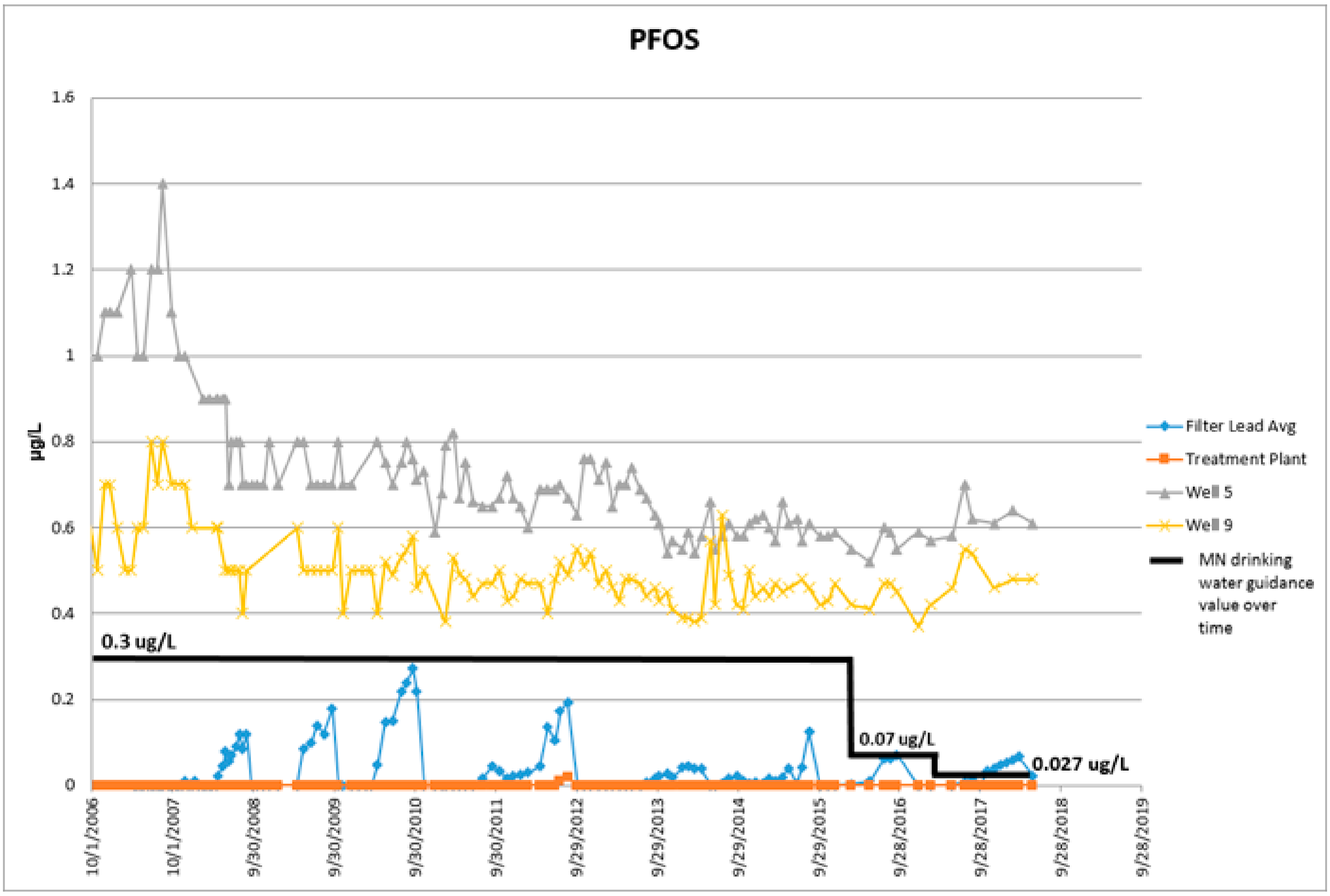


Figure 15-7. Influent and effluent concentrations for PFOS.

Source: Courtesy of the Minnesota Department of Health.

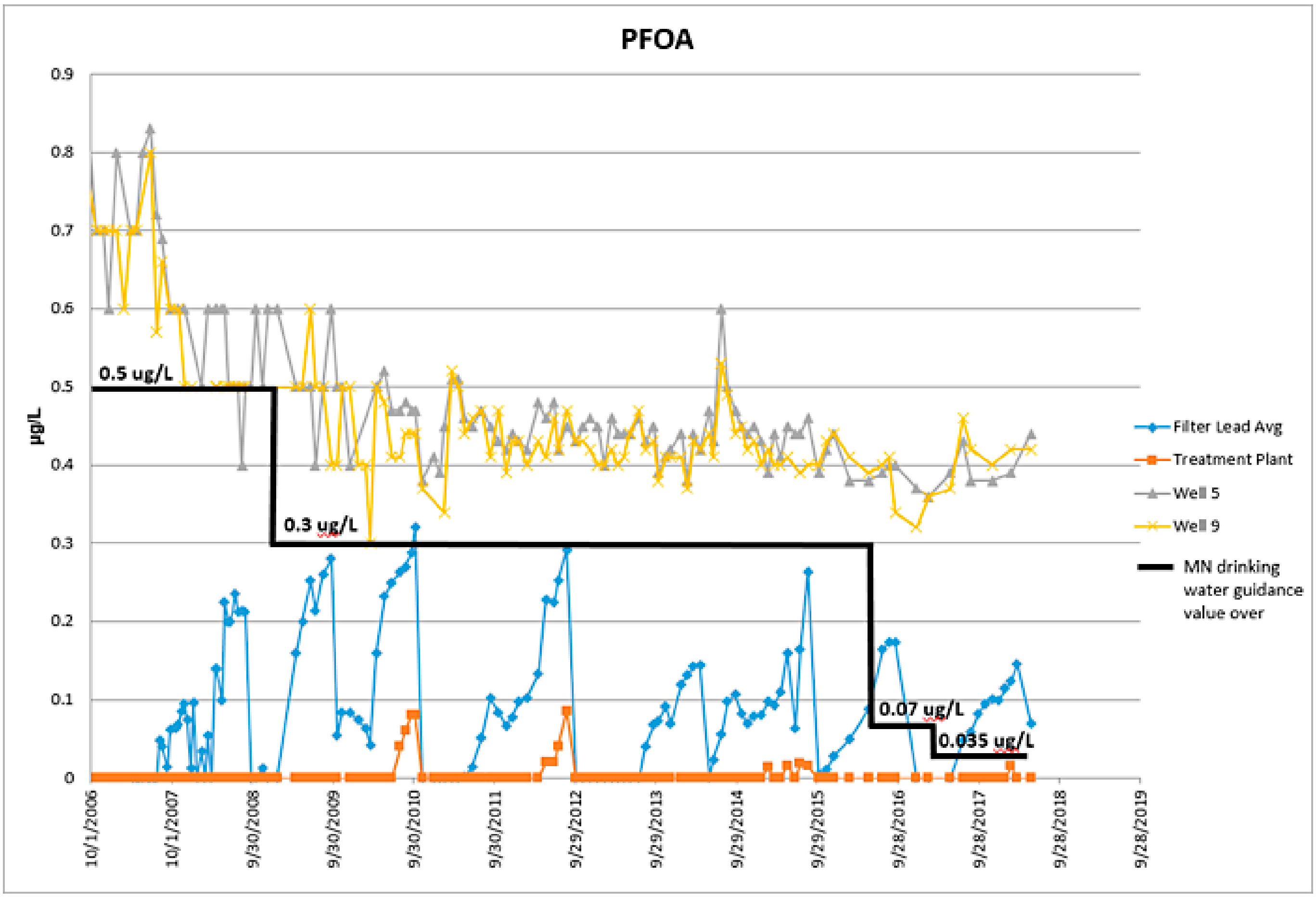


Figure 15-8. Influent and effluent concentrations for PFOA.
Source: Courtesy of the Minnesota Department of Health.

Costs

Capital costs for the GAC treatment facility were approximately $2.5 million. Annual operation and maintenance (O&M) costs, including sampling and GAC change-out, are approximately $250,000.

15.2.2 Ion Exchange (IX) Resins

Ion exchange resins can be utilized as single-use, where the media is disposed when it has reached the limit of its sorptive capacity, or regenerable, where the resin is regenerated and reused indefinitely (theoretically). The following two case studies outline field applications for these two related technologies.

15.2.2.1 Single-Use IX

Case Study: Horsham Township, Pennsylvania (Contributed by Francis Boodoo, Purolite Corporation, used with permission)

Background

The township of Horsham, Pennsylvania, located close to an AFFF release site, supplies drinking water to 7,800 residential, commercial, and industrial customers using 15 deep water wells. In 2014, five of the wells were confirmed to be impacted with PFAS. PFOS and PFOA were found in two wells at concentrations approaching the USEPA 2009 provisional health advisories (HAs) of 200 ppt and 400 ppt, respectively. These wells were immediately taken out of service. In June 2016, one month after EPA issued final HAs of 70 ppt for the combined concentrations of PFOS and PFOA, three more wells were removed from service due to elevated concentrations. The township began purchasing supplemental water from a nearby water supplier and began installing GAC filters to remediate and return the five impacted wells to service. Responding to consumer concerns, the township adopted an aggressive removal plan to reduce average PFOS/PFOA concentrations to less than 1 ppt (essentially to nondetect levels) in its entire water system by the end of 2016.

In addition to GAC filtration, the township started up a 50-gallon-per-minute selective ion exchange (IX) resin pilot in November 2016 on Well 10 to evaluate the performance of the resin in consistently reducing PFOS/PFOA to nondetect levels. A temporary 1-year permit was obtained from Pennsylvania Department of Environmental Protection (PA DEP) to install the resin pilot downstream of an existing GAC pilot that had been started up 20 days earlier. This was the first permit issued by the state of Pennsylvania for treating PFAS in drinking water using ion exchange resin.

Influent Water Characteristics

Influent concentration of a total of seven PFAS during the test period from November 2016 to August 2018 was an average of 103 ppt, a minimum of 78 ppt, and a maximum of 147 ppt. Individual PFAS concentrations are shown in Table 15-3. Average influent values for PFOS and PFOA were 34.1 and 20 ppt, respectively, somewhat lower than USEPA’s 70 ppt combined 2016 HA. Other influent geochemical parameters included sulfate at 8–23 ppm, nitrate at 10–11 ppm, alkalinity at 148–232 ppm, chloride at 35–50 ppm, pH at approximately 7.5, TDS at 296–358 ppm, suspended solids at 0.5–0.6 ppm, TOC at 0.2 ppm, and one sample detection for 1,1-dichloroethane at 37 ppt.

Table 15-3. Influent PFAS Characteristics of Well 10 *

	nanograms per liter (ng/L) (or parts per trillion (ppt))							
	PFBS	PFHpA	PFHxS	PFHxA	PFNA	PFOS	PFOA	Total PFAS
Lab Detection Level	1	1	2	1	2	2	1	
Minimum	6	4	17	6		27	13	78
Average	9	5	28	9		34	20	103
Maximum	14	8	41	13	2	48	40	147

* PFBS =perfluorobutanesulfonate; PFHpA = perfluoroheptanoate; PFHxA = perfluorohexanesulfonate; PFHxA = perfluorohexanoate; PFNA = perfluorononanoate, PFOS = perfluorooctanesulfonate, PFOA = perfluorooctanoate, PFAS = total poly- and perfluoroalkyl substances

Treatment Technology Design Details: GAC and Ion Exchange System

Well 10, with a peak design flow rate of 100 gpm, was used for large-scale piloting at a reduced flow rate of 50 gpm under the terms of the permit from PA DEP. The water was first passed through a 20-micron suspended solids filter, then in series through two 2.5-ft diameter stainless steel vessels, each vessel containing 20 cubic feet of bituminous GAC. EBCT for each charge of GAC amounted to 2.8 minutes or a total of 5.6 minutes for the two GAC vessels; linear velocity was approximately 10 gpm/ft^2. The township recognized that EBCT was lower than the 10–20 minutes specified in the PA Public Water Supply design manual and that linear velocity, even though it complied with the PWS, was higher than the typical 4 gpm/ft^2 used for GAC; however, the township and PA DEP considered the design acceptable for the low levels of PFAS measured and for the temporary nature of the pilot. After initial treatment by the GAC pilot, the water was passed through a 2.5-ft diameter vessel containing 20 cubic feet of Purolite Purofine PFA694E selective resin. Bed depths for both the GAC and resin media were approximately 34 inches. Sampling points were installed on the outlet of each vessel. An extra sampling point was installed in the resin polishing vessel at two-thirds of the resin bed depth. This allowed monitoring corresponding to EBCT of 1.8 minutes at the two-thirds sampling point and 2.8 minutes EBCT for the entire resin bed. The two-thirds sampling point would provide advanced notice of PFAS breakthrough.

System Performance

The entire system became operational on November 29, 2016. PFOS and PFOA sampled at the two-thirds point of the resin bed remained consistently at nondetect levels until rising to 2.6 ppt on day 394 and 4 ppt on day 472 (see Figure 15-9). For reporting purposes, the township decided to use a minimum reporting level of 2.5 ppt for each of PFOS and PFOA; values below the minimum reporting level would be considered nondetect. Once the PFOA concentration reached 2.6 ppt at the two-thirds sampling point for the resin, the treated water was diverted to the local sanitary sewer in keeping with the PA DEP permit. PA DEP has since granted permission to bypass the GAC system to enable performance evaluation of just the resin.

On day 514, with permission from PA DEP, the two GAC vessels were taken out of service while the raw water was routed directly to the resin vessel, which continued to operate. In this way, the performance of the resin could be evaluated without pretreating with the GAC. The resin operated for 639 days before PFOA was detected at a concentration of 2 ng/L of PFOA in an effluent sample from the resin bed. At that point the concentrations of PFBS, PFHxS, and PFOS were still at nondetect levels. Operating capacity of the resin at that point was equivalent to treating 511,000 bed volumes (BVs) of water based on two-thirds of the resin volume, or 329,000 BV based on the entire volume of resin.

Following successful and consistent performance of the resin-only system, PA DEP has issued an operating permit for use of resin only in a pair of lead-lag ion exchange vessels. Similar permits have also been issued at neighboring townships.

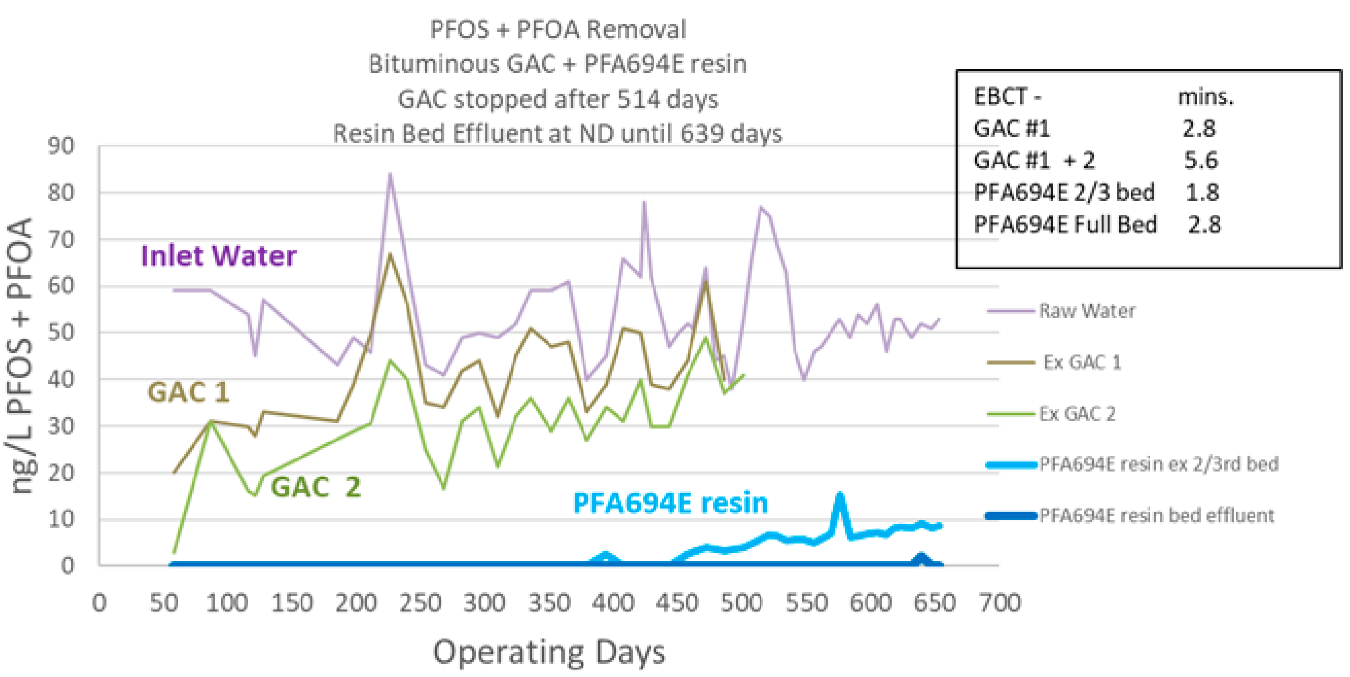


Figure 15-9. Combined PFOS/PFOA breakthrough.

Source: F. Boodoo, Purolite Corporation. Used with permission.

Even though PFOS and PFOA were the initial targets for reduction, consistent reduction of other short- and long-chain PFAS to nondetect levels was also achieved after passage through the resin. For conciseness, only total PFAS breakthrough graphs are shown in Figure 15-10, but the order of breakthrough observed was PFHxA < PFHpA < PFOA < PFNA < PFBS < PFHxS < PFOS.

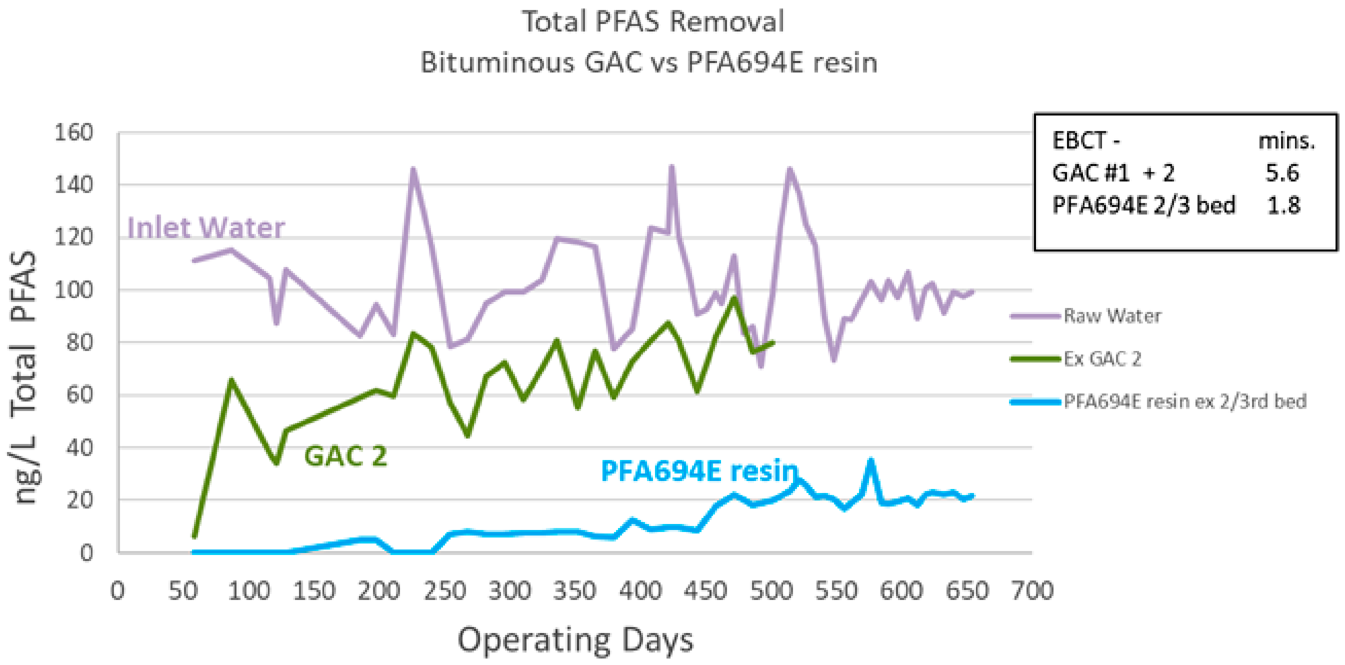


Figure 15-10. Combined breakthrough of total PFAS.

Source: F. Boodoo, Purolite Corporation. Used with permission.

Costs

The proposed permanent full-scale system is designed for a peak flow rate of 100 gpm with a pair of lead-lag vessels for the media. Design for ion exchange will include one 20-micron cartridge filter followed by two 4-ft diameter vessels with resin bed depth of 36 inches and EBCT of 2.8 minutes. Design for GAC will be one 20-micron cartridge filter followed by two 6-ft diameter vessels with GAC bed depth of 60 inches and EBCT of 10.6 minutes.

Annual operating cost, including replacement media, labor, trucking, spent media profiling, and incineration, is estimated at approximately $8,000 and $15,000, respectively, for ion exchange and GAC. These estimates are based on a very conservative operating capacity estimate of 350,000 BVs for a lead-lag pair of resin vessels; a generous capacity of 34,000 BVs is assumed for the GAC system. Operating costs are estimated at $0.16 and $0.29 per 1,000 gallons of water treated by the resin and GAC systems, respectively. Larger vessels needed for the GAC system will further add to the cost of using GAC versus the PFAS-selective resin.

15.2.2.2 Regenerable IX

Case Study: Regenerable Ion Exchange Resin Pilot Test and Full-Scale Application (Contributed by Steve Woodard, ECT2, and Nathan Hagelin, Wood Group, used with permission)

Background

The Air Force Civil Engineering Center (AFCEC) is conducting ongoing response activities to remove and remediate groundwater impacted by poly- and perfluoroalkyl substances (PFAS) at the former air force base in New Hampshire. The two primary PFAS found at the site are perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), at combined concentrations (PFOA+PFOS) above the 2016 USEPA lifetime health advisory (LHA) of 0.07 micrograms per liter (µg/l). In 2015, the USEPA issued an administrative order to establish maximum hydraulic containment of PFAS compounds to reduce source zone mass and mitigate migration of PFAS compounds to off-site receptors.

AFCEC responded by contracting with Wood Group, PLC, to conduct a side-by-side pilot test in 2016, comparing the performance of Emerging Compound Treatment Technologies' (ECT2) regenerable ion exchange (IX) resin and bituminous GAC. The resin outperformed GAC and was selected for full-scale implementation, mainly on its life cycle cost advantages, as determined by the results of the pilot study.

To evaluate the resin's ability to be regenerated, regeneration trials were conducted throughout the pilot test using a proprietary regeneration procedure with a solution of organic solvent and brine. Overall, PFAS removal results for the regenerated resin were consistent with new resin, as shown in Figure 15-9. Extended follow-on pilot testing utilized multicycling to confirm the effectiveness of the regeneration procedure to restore the resin's PFAS removal capacity. The regenerable resin system was selected for full-scale application, based on system performance and a favorable life cycle cost comparison.

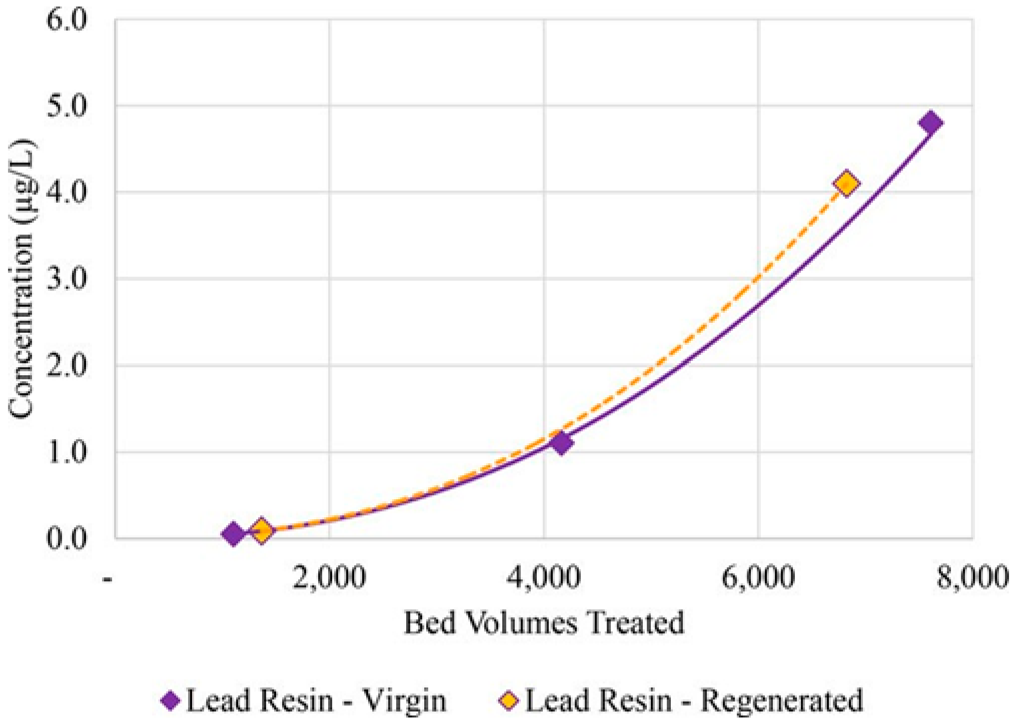


Figure 15-11. Postregeneration breakthrough curve (total PFAS).

Source: Steve Woodard, ECT2, and Nathan Hagelin, Wood Group, PLC. Used with permission.

Influent Water Characteristics

Table 15-4 provides a summary of influent PFAS concentrations observed throughout the pilot test. Total PFAS concentrations ranged from 65 to 112 µg/l, with an average of 94 µg/l. Average influent concentrations for PFOS and PFOA were 26 and 12 µg/l, respectively. Influent general chemistry parameters included pH of 6.8, alkalinity of 115 milligrams per liter (mg/l), TDS of 230 mg/l, total suspended solids of less than 2 to 5.6 mg/l, sulfate of 17 mg/l, TOC of 4.5 mg/l, and chloride ranging from 30 to 250 mg/l.

Table 15-4. Influent PFAS Concentrations

		Influent Concentration Observed During Pilot Test (µg/L)		
Analyte	**Analyte Acronym**	**Low**	**High**	**Average**
6:2 Fluorotelemer sulfonate	6:2 FTS	15	22	18
8:2 Fluorotelemer sulfonate	8:2 FTS	0.055	0.3	0.23
Perfluorobutane sulfonate	PFBS	0.81	1.3	1.1
Perfluorobutanoic acid	PFBA	0.89	2.1	1.3
Perfluoroheptane sulfonate	PFHpS	0.85	1.4	1.1
Perfluoroheptanoic acid	PFHpA	1.6	2.2	1.9
Perfluorohexane sulfonate	PFHxS	18	25	22
Perfluorohexanoic acid	PFHxA	5.9	8.9	7.7
Perfluorooctanoic acid	PFOA	9.1	13	12
Perfluorononanoic acid	PFNA	0.046	0.082	0.054

		Influent Concentration Observed During Pilot Test (µg/L)		
Perfluorooctane sulfonate	PFOS	4.2	32	26
Perfluoropentanoic acid	PFPeA	3.1	5.1	4.2
Sum of PFAS	–	65	112	94

Treatment Technology Design Details for Full-Scale System

The permanent full-scale resin system was designed for a maximum flow rate of 200 gpm (0.76 m^3/min), with influent total PFAS concentrations of approximately 90 µg/l. The primary project objective was to consistently produce treated water with combined PFOS plus PFOA concentrations below the 2016 USEPA lifetime health advisory (LHA) of 0.07 micrograms per liter (µg/l). The full-scale IX resin system was installed between fall 2017 and spring 2018, and the system officially commenced operation in April 2018.

Figure 15-12 shows a process flow diagram of the treatment system. The pretreatment portion includes bag filters to remove suspended solids and 6000-lb backwashable liquid GAC pretreatment filter to remove iron. The PFAS removal system consists of two parallel trains of lead-lag regenerable IX resin vessels, each 86″ tall x 36″ diameter, packed with 49 cubic feet of ECT's SORBIX A3F regenerable resin. These vessels are designed to operate up-flow during normal operation, and down-flow during regeneration. Two parallel, 86″ tall x 36″ diameter polish vessels are filled with IX resin for PFAS polishing, including short chains. The polish vessels operate in the down-flow mode and contain a blend of IX resins tailored to the general water chemistry and PFAS species and their relative concentrations.

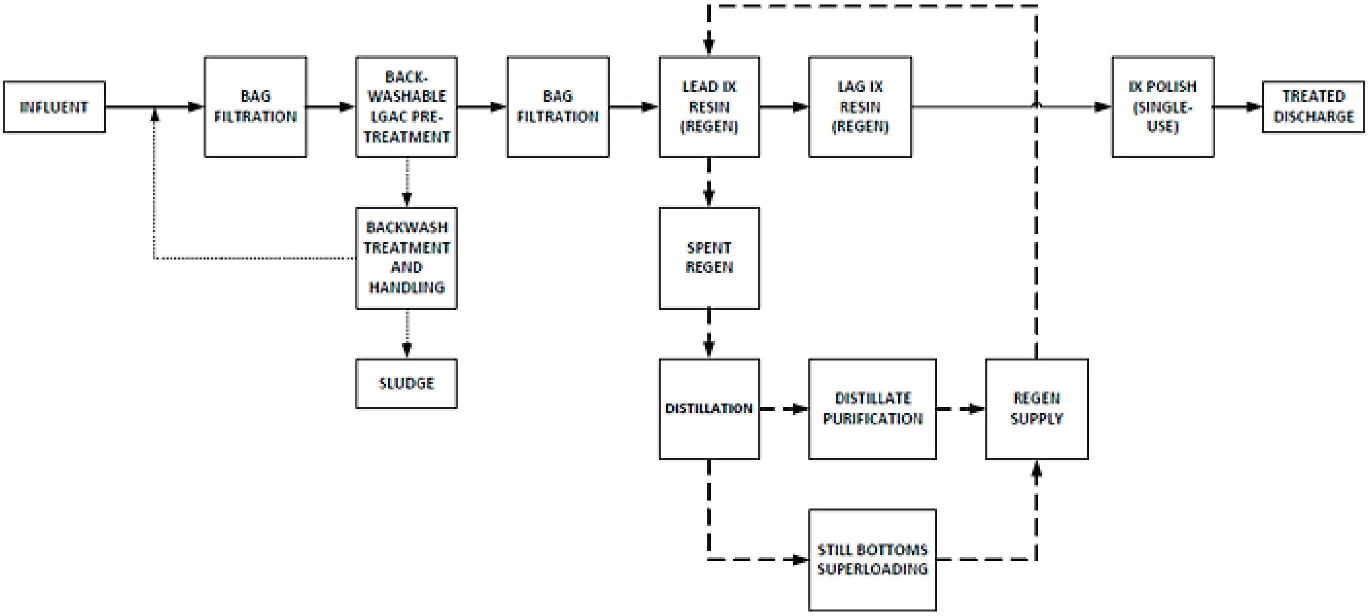


Figure 15-12. Block flow diagram of full-scale treatment system.

Source: Steve Woodard, ECT2, and Nathan Hagelin, Wood Group, PLC. Used with permission.

The in-vessel regeneration system (Figures 15-13 and 15-14) consists of a regenerant solution holding tank and pump skid. The regenerant solution is a mixture of organic solvent and brine, which effectively strips PFAS from the IX resin and then flows into a spent regenerant holding tank. The spent regenerant is recycled for reuse in the next regeneration cycle by using a distillation and super-loading process. First, the spent regenerant is transferred to a solvent recovery unit. Solvent makes up the majority of the regenerant solution and is recovered through distillation, given its low boiling point relative to water, and transferred to the regenerant supply tank for reuse in the next regeneration cycle. The remaining distillate residue, known as the "still bottoms," is a low-volume, high PFAS concentration brine solution. The still bottoms are pumped through super-loader vessels that contain a proprietary resin blend, transferring the PFAS mass onto the super-loaded media. Super-loading is the process by which a relatively small volume of highly concentrated PFAS solution is passed very slowly through a small volume of media. The long EBCT approaches equilibrium (isotherm) conditions, thereby maximizing PFAS mass transfer onto the media and minimizing the amount of solid waste requiring disposal or incineration.

Figure 15-13. Regenerable and polish IX resin vessel skids.

Source: Steve Woodard, ECT2, and Nathan Hagelin, Wood Group, PLC. Used with permission.

Figure 15-14. Resin regeneration system.

Source: Steve Woodard, ECT2, and Nathan Hagelin, Wood Group, PLC. Used with permission

System Performance

The PFAS remediation system has been successfully treating the groundwater since system start-up in April (Figure 15-15). Through December 2018, the effluent water quality from the IX resin system has been consistently nondetect for the monitored PFAS compounds, including the short-chain species, readily achieving compliance with the treatment objective of 0.70 µg/l LHA target for PFOS and PFOA. Although 6:2 FTS has not been detected in samples collected from the IX vessel effluent, it has been detected in the system effluent and is believed to be the result of transformation processes that are not yet understood.

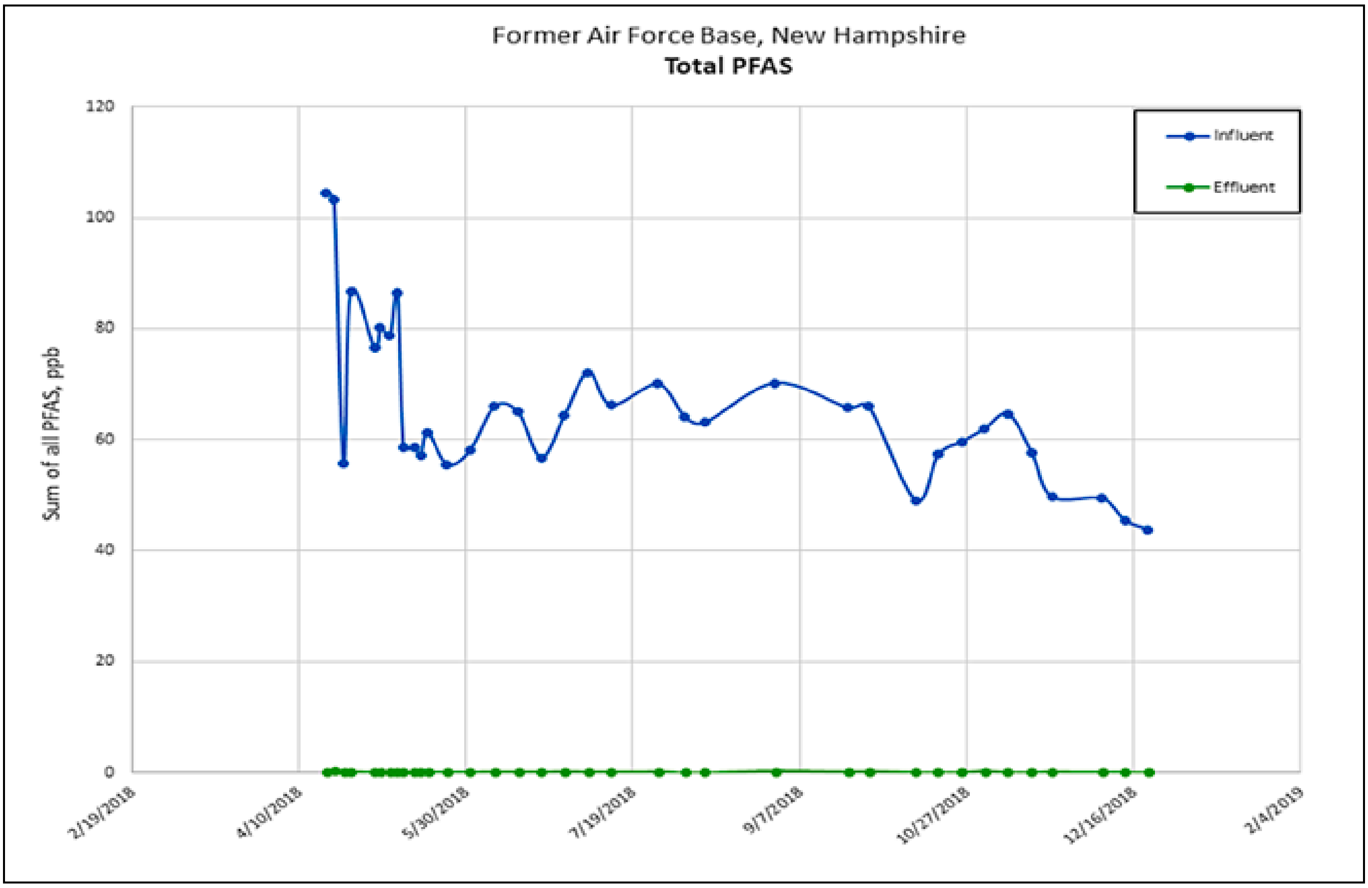


Figure 15-15. Influent and treated effluent total PFAS concentrations.

Source: Steve Woodard, ECT2, and Nathan Hagelin, Wood Group, used with permission

The system has been operated in the 35- to 70-gpm range since start-up, somewhat less than the design flow rate. This has been done to accommodate higher than anticipated influent iron concentrations that have resulted in the requirement for frequent bag filter change-outs. The resulting extended EBCTs in both the backwashable GAC pretreatment vessel and the IX resin vessels have resulted in better than projected PFAS removals. Also, the resin regeneration schedule has been modified to accommodate the lower flow rate by removing one of the two parallel trains from service. This has allowed the resin vessels to be loaded closer to design values. Four resin regenerations have been performed successfully through December 2018; however, the IX media regenerated through December 2018 was not loaded to the full design capacity due to the reduced flow during early operation. Operational modifications have been made to address and correct minor challenges with the distillation system, and regenerant recovery and super-loading processes have proven successful. The original super-loading media is still operational, having removed and concentrated greater than 99.99% of the recovered PFAS mass; therefore, no PFAS waste has needed to be hauled off site to date.

Costs

The capital cost for the regenerable IX was $2.9M for *all* treatment equipment, process piping, pumps, instrumentation, and system electrical. It does not include project management, construction management, the extraction network and field piping, or the building and building mechanical or electrical systems.

15.2.3 Colloidal Activated Carbon

Case Study: In Situ Colloidal Activated Carbon—PFAS in Groundwater in Crawford County, Michigan (Contributed by Scott Wilson, Regenesis, used with permission)

Background

Since the late 1980s, the Michigan Department of Military and Veterans Affairs (DMVA) has been implementing a range of technologies to remediate groundwater impacted by chlorinated solvents at Camp Grayling in Crawford County, Michigan, a year-round training center for the Michigan Army National Guard (MIARNG). In 2016, the DMVA became aware of the

]

potential contamination of PFAS from past operations such as on-site firefighting training at Grayling Army Airfield (GAAF). Groundwater testing revealed PFAS commingled with chlorinated solvents migrating toward the property boundary. The impacted groundwater was shallow at 15 feet below ground surface (bgs) and was shown to be moving at a velocity of about 250 ft/yr through a sandy gravel aquifer. Sensitive downgradient receptors included numerous residences and surface water bodies. See also Regenesis (2020) for more information.

Contaminant Characteristics

Target groundwater contaminants at the GAAF site included PFAS (PFOS and PFHxS) at a combined concentration of about 130 ng/L commingled with perchloroethylene (PCE), which was present at a concentration of about 10 ug/L. Data from dedicated passive flux samplers deployed at the project site indicated that groundwater contamination was primarily existing in a sandy contaminant flux zone located between 15 and 27 feet bgs.

Regulatory Involvement

The DMVA decided to perform a demonstration of in situ colloidal activated carbon (CAC) technology to treat the PFAS and PCE contamination at the GAAF site. This demonstration consisted of injecting CAC into a zone of the contaminated aquifer and actively monitoring groundwater moving through the treatment area. The primary reason DMVA chose this approach was its proven performance on other project sites where it rapidly removed PFAS from the dissolved phase and was expected to perform for decades with a single application. “Additionally, the project life-cycle cost was a consideration for the DMVA in their selection. The projected cost for installing” an in situ CAC treatment zone in the subsurface was significantly lower than installing and “operating a mechanical system over a similar timeframe” (Regenesis 2020).

Treatment Technology

CAC is composed of very fine particles of activated carbon (1–2 µm) suspended in water using organic polymer dispersion chemistry. When the CAC material is injected into the subsurface, the carbon particles bind to the aquifer matrix but do not obstruct pore throats. Groundwater flows through the treatment zone. Organic compounds such as PFAS sorb on to the carbon particles, removing them from groundwater.

To determine the amount of CAC required for the demonstration, a proprietary finite-difference model was used to determine dosing of carbon, expected contaminant retardation/competitive sorption, and expected performance longevity. The model accounts for site-specific factors such as hydrogeology and contaminant flux while considering competitive sorption and biodegradation (in the case of PCE) to determine the quantity of CAC required.

Ultimately “the application design consisted of a single row of nine direct push injection points positioned upgradient of a previously installed monitoring well, MW-29” (Regenesis 2020). The total amount of CAC injected was 2,400 lbs of a 4% (w/w) suspension and 2,400 lbs of a 20% (w/w) suspension. “The injection line was configured as an arc to account for temporal and spatial variability in the groundwater flow direction. Initially two downgradient well pairs (MW-29/29C and MW-29D/29E) were placed 6 feet and 16 feet downgradient of the barrier, respectively, to monitor the pilot test performance. Each well of a well pair was installed with a 5-feet screened section to monitor the upper and lower treatment interval sections” (Regenesis 2020). Figure 15-16 shows the monitoring well layout.

“The vertical injection interval was specified from 15 to 27 feet below the ground surface (bgs) to match the PFAS flux zone and accommodate seasonal water table fluctuations. In the pilot test area, this PFAS flux zone predominantly comprised of sand and gravel overlying a clay layer” (Regenesis 2020).

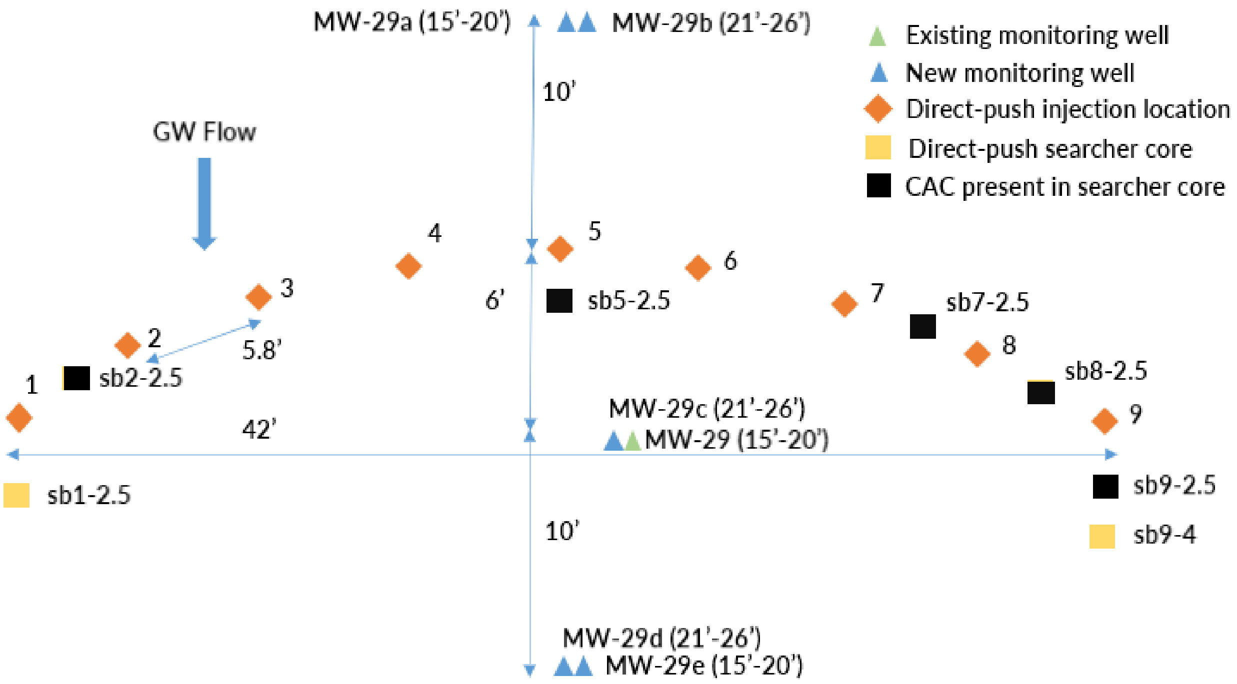


Figure 15-16. Wells used for the CAC demonstration project. Note that the values after the dash in the "sb" points are the distance from the injection point.
Source: Scott Wilson, Regenesis, used with permission.

Injection of the CAC zone commenced in October 2018. Subsurface CAC distribution was optimized during injection by "adjusting injection variables including flow rate, screen size, injection volume, and injection point positioning" (Regenesis 2020). Verification of required CAC distribution was achieved "by collecting soil cores and groundwater samples from temporary piezometers placed between injection points. The soil cores revealed consistent CAC distribution over the target interval, while the groundwater samples collected from the piezometers indicated" (Regenesis 2020) required CAC presence in groundwater (Figure 15-17).

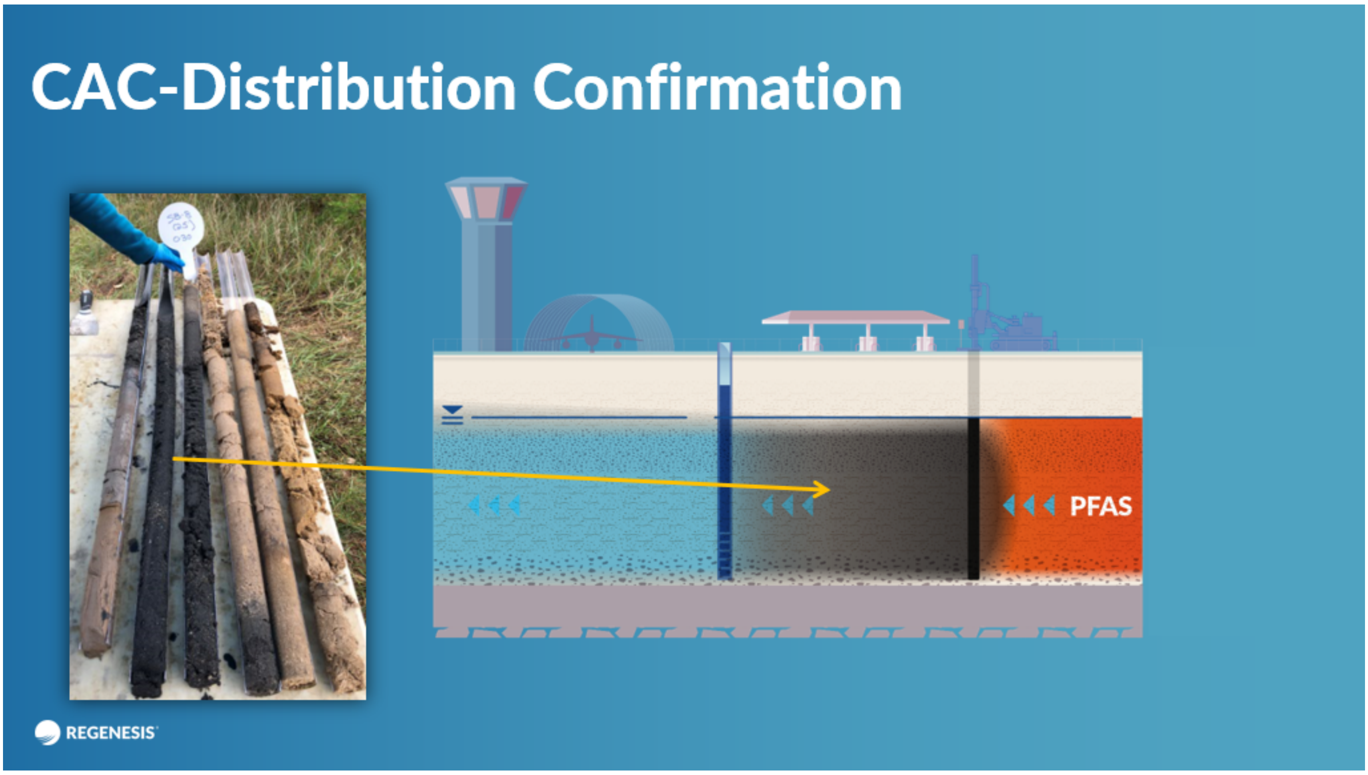

CAC-Distribution Confirmation

Figure 15-17. Vertical sections of a "searcher core" verifying the presence of CAC at the interval between 15

and 28 feet bgs.

Source: Scott Wilson, Regenesis, used with permission.

System Performance

By the first sampling event, approximately one month after injection, the CAC zone treatment had reduced PFAS “to concentrations below the standard method detection limit of 10 nanograms per liter (ng/L) in downgradient wells. Initial reductions were also observed in upgradient well-pair (MW-29A/B), indicating potential injection influence. However, by the second event, approximately two months after injection, concentrations in these upgradient wells had begun to rebound while the downgradient wells remained at non-detect” (Regenesis 2020). Since then, the CAC treatment has maintained PFAS concentrations below 10 ng/L in the downgradient wells for 3.5 years. Figure 15-18 includes PFAS concentration data for upgradient and downgradient well pairs.

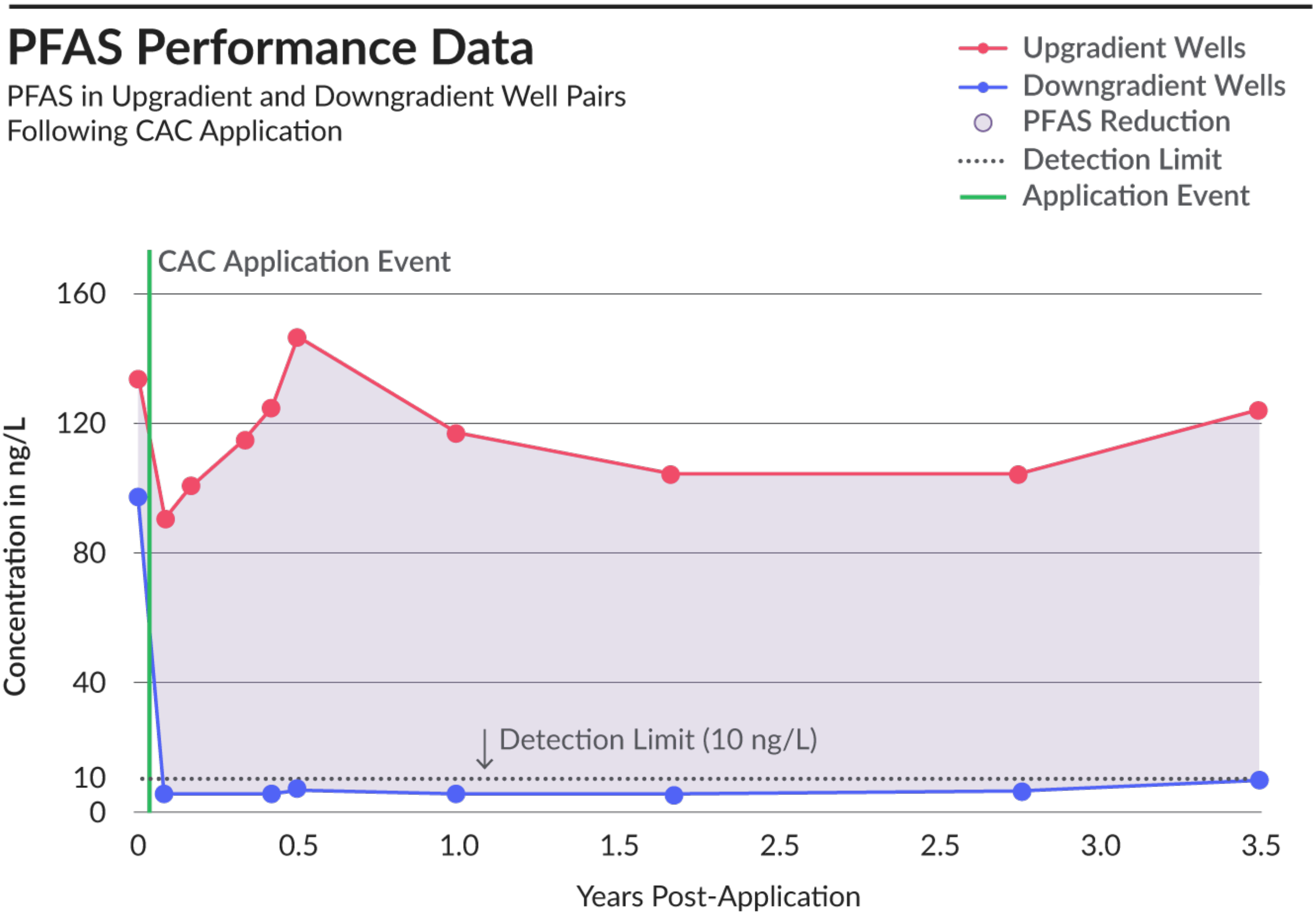


Figure 15-18. PFAS reductions as an average of monitoring well concentrations downgradient of CAC-treated zone.

Source: Scott Wilson, Regenesis, used with permission.

PCE concentrations followed a similar pattern as PFAS: reduction to nondetect (1 microgram per liter) by the first month, followed by sustained nondetect levels. Figure 15-19 includes PCE concentration data for upgradient and downgradient well pairs.

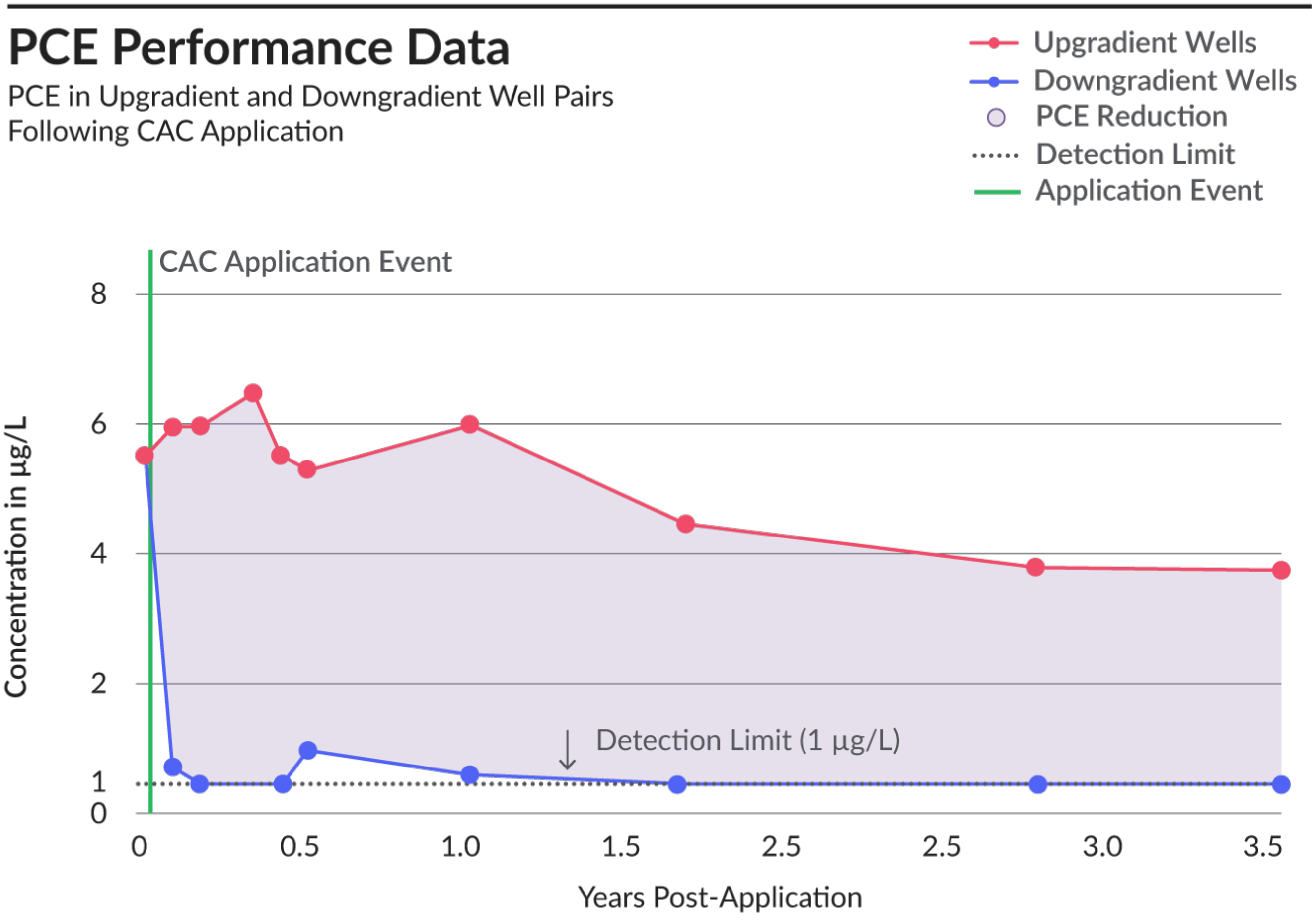


Figure 15-19. PCE reductions as an average of monitoring well concentrations downgradient of CAC-treated zone.

Source: Scott Wilson, Regenesis, used with permission.

The CAC demonstration has achieved all the remedial objectives to date (3.5 years) while modeling predictions suggest that the CAC installed will continue to remove PFAS and PCE for decades. Based on this demonstration project, the Michigan DMVA is considering expanded use of in situ CAC technology at other sites.

Cost

The total installation cost of the demonstration project was about $55,000, including the CAC material cost of $28,000 and field labor/subcontracting cost of about $27,000. There is no operation or maintenance cost. Sampling and analysis totals about $6,200 per year.

15.2.4 Foam Fractionation

15.2.4.1 Ex situ Groundwater Treatment

Case Study: Field Trial Conducted for the Australian Department of Defence (2019-2021) in Queensland, Australia (Contributed by David Burns, EPOC Systems)

EPOC Enviro LLC (USA), a subsidiary of OPEC Systems (Australia), was contracted by the Australian Department of Defence to provide a groundwater treatment field trial plant at the Army Aviation Centre Oakey in Queensland, Australia. The field trial project was managed by WSP with project management and contract administration provided by GHD. The field trial plant required a design capacity to treat 250 m3/day (2.9l/sec or 46 gpm) to remove PFAS from groundwater, which included the primary treatment technology known as Surface-Active Foam Fractionation (SAFF®) and paired with an anion exchange (AIX) resin polishing treatment to ensure compliance with Australian and New Zealand Heads of EPAs (HEPA) drinking water guideline criteria prescribed by the PFAS National Environmental Management Plan (NEMP, V2, Jan. 2020). Groundwater had

historically been contaminated by AFFF discharges from 1977 to 2005. Following the 3-year field trial, the Australian Department of Defence subsequently awarded a continuation of the groundwater treatment plant contract with increased treatment capacity of 345 m3/day (4.0l/sec or 63 gpm) and an expanded irrigation network.
A full case study is provided in the Burns et al. (2021) article, “PFAS Removal from Groundwaters using Surface-Active Foam Fractionation.” https://onlinelibrary.wiley.com/doi/10.1002/rem.21694.

15.2.4.2 Ex situ Landfill Leachate Treatment

Case Study: Field Trial Conducted for Telge Återvinning AB, Sweden (2021–2022) (Contributed by David Burns, EPOC Systems)

EPOC Enviro LLC (USA), a subsidiary of OPEC Systems (Australia), was contracted by Telge Återvinning AB to provide a containerized treatment plant to treat leachate at the Telge Recycling Plant in Sweden. The initial field trial and project management were provided by EnvyTech Solutions AB. The treatment plant required a design capacity to treat 500 m3/day (5.8l/sec or 92gpm) to remove PFOS from landfill leachate water using Surface-Active Foam Fractionation (SAFF®) without any pretreatment or polishing treatments. The leachate, which exhibited a complex background chemistry including algal/zooplankton content, suspended solids, total organic carbon, and other organic and inorganic contaminants, was contained in a catchment pond with a volume of approximately 15,000 m3. A direct feed line drew water from the leachate pond to the SAFF® treatment plant using a submerged pump located approximately 1.5 m below the surface. The system achieved average treatment results for PFOS ≤2.34 ng/L, PFHxS ≤1.00 ng/L, and PFOA ≤1.28 ng/L, corresponding to removal percentages of ≥98.7%, ≥98.8%, & ≥99.7%, respectively. The mean concentration of PFOS was below 50 ng/L, which is defined by the voluntary Scandinavian REVAQ guideline.

A full case study is provided in the Burns et al. (2022) article, “Commercial-scale remediation of per- and polyfluoroalkyl substances from a landfill leachate catchment using Surface-Active Foam Fractionation (SAFF®): https://doi.org/10.1002/rem.21720.

15.3 Risk Assessment Case Study

The New Jersey Department of Environmental Protection (NJDEP) Division of Science, Research, and Environmental Health conducted an initial assessment of PFAS impacts at a select group of surface water bodies in New Jersey (NJDEP 2018) (Figure 15-20). The results of fish tissue sampling from each site were used in a risk assessment methodology to determine the need for fish consumption advisories for PFAS in each of those water bodies.

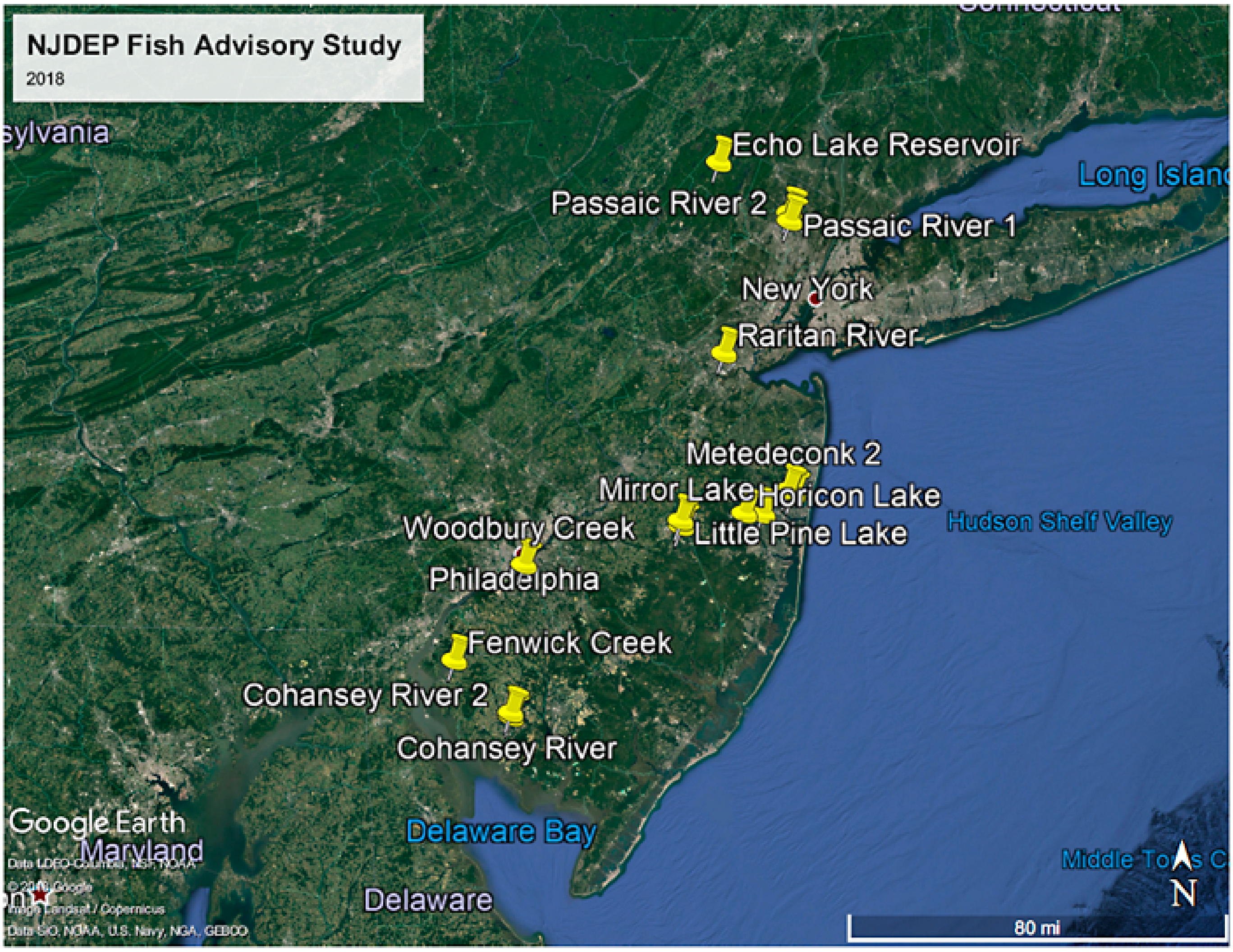
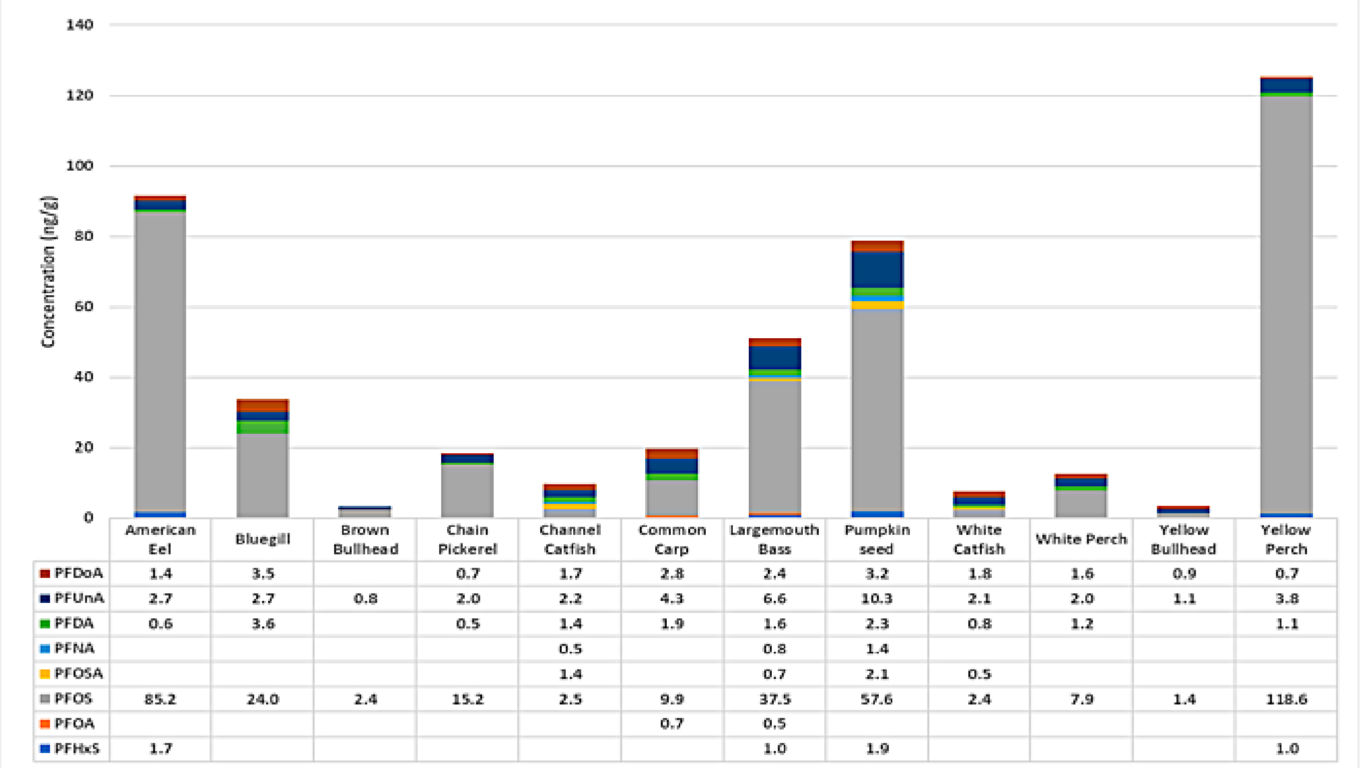


Figure 15-20. Map of water bodies included in NJDEP fish tissue study.

Overall, fish tissue samples from up to 12 different species were collected from 11 specific water bodies throughout the state. The water bodies were selected for sampling based upon their location relative to possible PFAS sources and the likelihood that they could be used for recreational fishing. Samples were analyzed for 13 PFAS (PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnA, PFDoA, PFBS, PFHxS, PFOS, and PFOSA), and as presented in Figure 15-21, the results indicated that the predominant PFAS detected in the fish tissues was PFOS.



	American Eel	Bluegill	Brown Bullhead	Chain Pickerel	Channel Catfish	Common Carp	Largemouth Bass	Pumpkin seed	White Catfish	White Perch	Yellow Bullhead	Yellow Perch
🟥 PFDoA	1.4	3.5		0.7	1.7	2.8	2.4	3.2	1.8	1.6	0.9	0.7
■ PFUnA	2.7	2.7	0.8	2.0	2.2	4.3	6.6	10.3	2.1	2.0	1.1	3.8
🟩 PFDA	0.6	3.6		0.5	1.4	1.9	1.6	2.3	0.8	1.2		1.1
🟦 PFNA					0.5		0.8	1.4				
🟨 PFOSA					1.4		0.7	2.1	0.5			
▨ PFOS	85.2	24.0	2.4	15.2	2.5	9.9	37.5	57.6	2.4	7.9	1.4	118.6
🟧 PFOA						0.7	0.5					
🟦 PFHxS	1.7						1.0	1.9				1.0

Figure 15-21. Fish tissue sampling results. Average concentration detected per species.

Data from NJDEP (2018).

Using the noncancer oral reference doses (RfDs) New Jersey Department of Environmental Protection derived for PFOA [2 ng/kg-day; (NJDWQI 2017)], PFOS [1.8 ng/kg-day; (NJDWQI, 2018)], and PFNA [0.74 ng/kg-day; (NJDWQI 2015)], and generic conservative assumptions regarding fish consumption exposure, NJDEP derived risk-based advisory triggers for each of these compounds based upon different fish consumption frequencies specifically, once/day, once/week, once/month, once/3 months, once/year.

The following equation was used to derive their risk-based triggers (which are presented in Figure 15-22):

$$C_{fish} = HQ \cdot RfD \left(\frac{BW \cdot AT_{nc}}{M \cdot CR} \right)$$

where

– C_{fish} is the risk-based fish concentration (ng/g)

– HQ is the target hazard quotient = 1 (unitless)

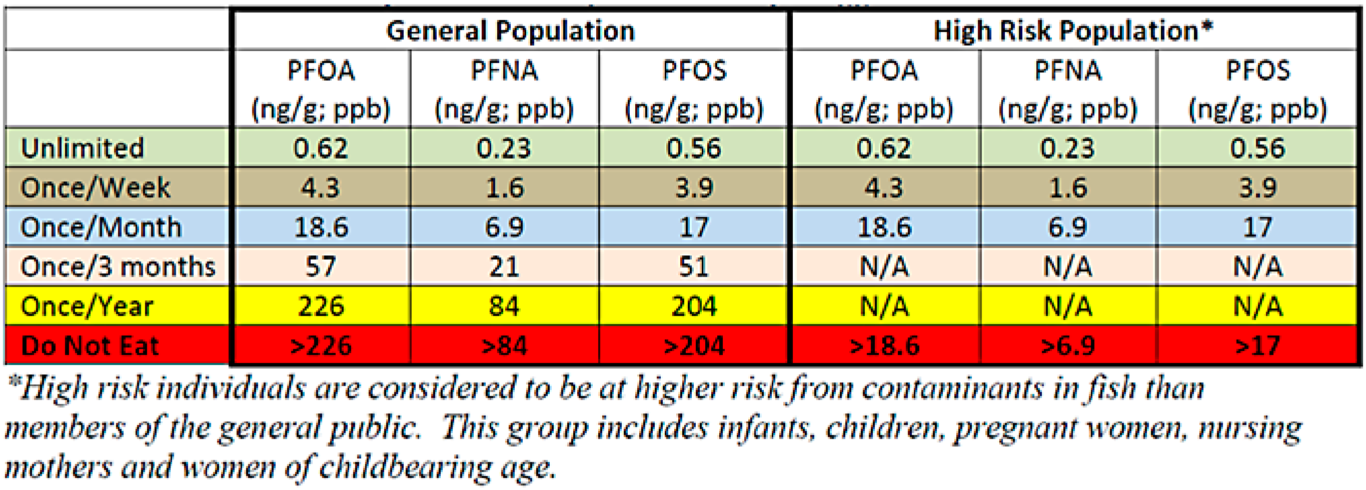
– M is the number of meals during the exposure period

– CR is the fish consumption rate (g/meal) = 8 oz/meal (227 gram/meal)

– BW is the body weight (kg) = 70 kg

– RfD is the chemical-specific oral reference dose (ng/kg-day)

– AT_{nc} is the noncancer averaging time (days)



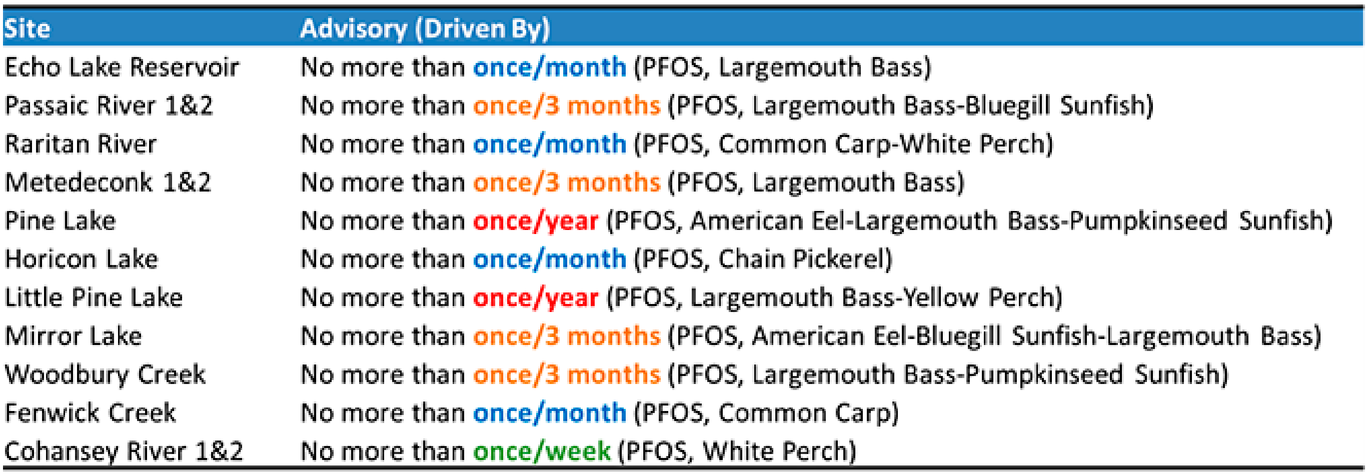
	General Population			High Risk Population*		
	PFOA (ng/g; ppb)	PFNA (ng/g; ppb)	PFOS (ng/g; ppb)	PFOA (ng/g; ppb)	PFNA (ng/g; ppb)	PFOS (ng/g; ppb)
Unlimited	0.62	0.23	0.56	0.62	0.23	0.56
Once/Week	4.3	1.6	3.9	4.3	1.6	3.9
Once/Month	18.6	6.9	17	18.6	6.9	17
Once/3 months	57	21	51	N/A	N/A	N/A
Once/Year	226	84	204	N/A	N/A	N/A
Do Not Eat	>226	>84	>204	>18.6	>6.9	>17

**High risk individuals are considered to be at higher risk from contaminants in fish than members of the general public. This group includes infants, children, pregnant women, nursing mothers and women of childbearing age.*

Figure 15-22. Risk-based fish advisory triggers.
Data from NJDEP (2018).

Because of concerns associated with the potential developmental health effects associated with these chemicals and given a lack of acute toxicity values for these compounds, NJDEP did not recommend advisory levels for the once/3 months and once/year exposure frequencies for high risj populations (young children, pregnant and lactating women, women of childbearing age), and the once/month value is the least frequent consumption category recommended for these high risk populations.

A comparison of the derived risk-based advisory levels with the measured concentrations in fish tissue samples from each of these waterways resulted in NJDEP recommending the following fish consumption advisories for the general population (Figure 15-23).



Site	Advisory (Driven By)
Echo Lake Reservoir	No more than once/month (PFOS, Largemouth Bass)
Passaic River 1&2	No more than once/3 months (PFOS, Largemouth Bass-Bluegill Sunfish)
Raritan River	No more than once/month (PFOS, Common Carp-White Perch)
Metedeconk 1&2	No more than once/3 months (PFOS, Largemouth Bass)
Pine Lake	No more than once/year (PFOS, American Eel-Largemouth Bass-Pumpkinseed Sunfish)
Horicon Lake	No more than once/month (PFOS, Chain Pickerel)
Little Pine Lake	No more than once/year (PFOS, Largemouth Bass-Yellow Perch)
Mirror Lake	No more than once/3 months (PFOS, American Eel-Bluegill Sunfish-Largemouth Bass)
Woodbury Creek	No more than once/3 months (PFOS, Largemouth Bass-Pumpkinseed Sunfish)
Fenwick Creek	No more than once/month (PFOS, Common Carp)
Cohansey River 1&2	No more than once/week (PFOS, White Perch)

Figure 15-23. NJDEP fish advisories for general population.
Data from NJDEP (2018).

15.4 Risk Communication Case Studies

15.4.1 Little Hocking Water Association (LHWA), Ohio

The communication and community participation strategy used for residents served by the Little Hocking Water Association (LHWA) in southwest Ohio produced effective results in motivating actions by individuals, government, and industry which led to a significant, measurable reduction in residents’ blood PFOA levels.

A community-first strategy was implemented at the Little Hocking, Ohio, site to effectively communicate scientific results and findings in a manner that embodies the principles of community-based participatory research (CBPR). This type of strategy combines scientific methodology with community capacity-building strategies to address the disparities and power imbalances among stakeholder groups (business owners, residents, regulatory, and responsible party). If properly implemented, CBPR can result in trust rebuilding, management of environmental justice matters, empowerment to those affected by providing information for informed action, and improved research and data collection (Viswanathan et al. 2004; Hartwig, Calleson, and Williams 2006; O'Fallon, Tyson, and Dearry 2000; Executive Order 12898 1994). The following is a case study summary of the Little Hocking, Ohio, site (Emmett et al. 2006; Emmett et al. 2009; Emmett and Desai 2010).

15.4.1.1 Site Description

The LHWA is a rural water authority that serves several small communities with a total population of approximately 12,000 residents in 4,000 households. The reticulation system extends around 25 miles into Ohio from Little Hocking, a small rural community along the Ohio River in Washington County, Appalachian Ohio. Based on the 2010 U.S. Census, the total population of Little Hocking was 263, predominately Caucasian, majority between the ages of 18–64 years, and 21.5% of individuals live below the poverty level. The water intake wells for the LHWA are located directly across the Ohio River from a Teflon production plant that used ammonium perfluorooctanoate (APFO, the ammonium salt of PFOA). This plant was physically located in West Virginia; therefore, the enforcement and regulation of the plant and its emissions fell to the West Virginia agencies.

Since the 1950, the plant was known to historically release APFO into the air and water and to dispose of byproducts containing APFO in local landfills (WV DEP 2002). APFO readily converts to its anionic form, PFOA, in the environment. When tested in 2001 and 2002, the LHWA source wells had levels ranging from 0.855 ppb to 7.69 ppb. Community concerns were raised because PFOA detections in the water supply were considerably higher than any reported PWS in the United States at the time. Prior to the study summarized here, there was no information about the sources of PFOA that was being detected in human blood in widespread locations. In the absence of this information, the West Virginia Department of Environmental Protection convened the C-8 Assessment of Toxicity Team, and developed a health protective screening level for water at 150 ppb. In addition, an interim action level of 14 ppb was established by a USEPA Consent Order with the responsible party. In August 2002, groundwater borings advanced in the LHWA well field contained PFOA concentrations up to 78 ppb. A class action suit was initiated, and distrust increased among the affected community and both the government and responsible party.

To investigate community concerns about potential PFOA contamination of residents in the LHWA district, a partnership was formed between the University of Pennsylvania School of Medicine, a local health provider, and the Decatur Community Association, made up of residents living within the LHWA district. The partnership obtained an environmental justice research grant from the National Institute of Environmental Health Sciences. The research was designed to engage the affected community on all aspects of the study to determine (1) whether blood PFOA levels were elevated in the community, compared with Philadelphia residents and with published population values; (2) if blood PFOA levels were elevated, was the source air, water, or some other combination of exposures; and (3) if levels were elevated, were there changes in certain biomarkers of potential toxic effects.

A community advisory committee (CAC) was formed with local residents served by the water supply, local physicians, state and federal government representatives, a health researcher, and a school system representative. A community project coordinator was employed as a communication enabler. The CAC met quarterly and all meetings were open to the public with the only participation restrictions being that the attorneys and plant representatives were not permitted to take part in the discussions. Community advice was particularly sought as to which scientific questions to address, development and wording of questionnaires, communications with residents, and citizen concerns. The CAC utilized newsletters to keep local residents and other stakeholders informed. These newsletters and CAC meeting minutes were posted on a CAC study website.

The study team collected blood serum PFOA, hematologic and biochemical biomarkers, a questionnaire to obtain information on demographic and occupational information, and health conditions from a stratified random sample of residents in the LHWA reticulation area. The median blood PFOA levels for residents were approximately 80 times those of the general population and similar to levels reported for production workers at the fluoropolymer facility. PFOA levels were higher in children and the elderly. Residents using LHWA water who worked in production areas of the plant had PFOA levels that reflected additive effects from both exposure pathways. Residents who primarily used well water for domestic purposes had PFOA levels that correlated with the PFOA concentration in well water. No impact was seen from living in areas with higher estimated air levels.

15.4.1.2 Community-First Communication Strategy

After data had been collected from participants, but before any results were available, the CAC discussed and developed a communication strategy. For this purpose, the CAC developed a set of general principles for communication and a list of priority targets representing the community's preferred order for communication of results:

LHWA Residents' General Principles for Communications, from Emmett and Desai (2010) and Emmett et al. (2009).

- Results should be released promptly, but not before the investigators are comfortable in doing so.
- Individual participants should receive their results first to avoid participants first learning study results from the press, neighbors, or friends.
- The press should be informed in a manner that is both timely and allows the investigators to control the message as much as possible.
- The study must remain a credible source of information.
- Communications should maximize constructive responses to the findings.
- Communications should minimize pointless concern.
- Questions from individuals should be answered promptly.

LHWA District Residents' List of Priority Targets for Communication of Results, from Emmett et al. (2009).

- study participants and community (residents of the water district)
- community advisory committee
- relevant authorities and representatives (county and state health departments, state Department of Environmental Protection, local water authorities, state and federal elected government representatives for the area, local townships, sheriffs' departments, USEPA)
- local medical providers
- local media
- national media, as necessary.

Once the general principles of engagement were established, the CAC developed a communication strategy and plan. The CAC determined that the strategy required multiple modes of engagement that enforced consistent simple messages and consideration of careful timing to mitigate development of inaccurate perception of risk and management strategies. The communication plan was a "living document" to facilitate continued integration of stakeholder input, regulatory development, and scientific advancement. The sequence of communications commenced with mailings to participants at the end of July 2005 and culminated in a community meeting on August 15, 2005, where full results were presented.

15.4.1.3 Results and Use of Risk Communication Tools

1. *Notifications to Participants and Authorities*—Biomonitoring results were sent via next-day-delivery mailings to individual study participants. These results included the individual's blood PFOA and biomarker levels as well as comparative information on PFOA levels (including blood levels for national and site facility workers, general US population, and community neighborhoods) and a toll-free telephone number to contact a study physician with any questions. Letters containing aggregated, not individual, results were sent simultaneously to identified authorities and CAC members, to ensure that recipients would be able to respond appropriately to inquiries from the public.
    - *Lessons and Takeaways*: Calls often needed to be returned after business hours. Most concerns focused on higher levels in children and the elderly, and possible interactions of elevated PFOA levels and particular medical conditions.
2. *Initial Press Release and Briefing*—Key local and regional media were identified and informed of the communication plan around the date the participant letters were sent. An initial press release and briefing were made the second day after the results were mailed to ensure that participants did not first learn of the issue through the press, while still providing investigators an opportunity to be the primary source of information to the press. Identified media representatives and national news outlets were invited to the news briefing. The release simply identified that levels in LHWA residents were much higher than those in the general US population, and that water had been identified as the major source of exposure. Interested stakeholders were urged to attend a community meeting where comprehensive results would be released and discussed.
    - *Lessons and Takeaways:* The reporting by local and national media did not misconstrue information and local media participated as per the communication plan. The CAC perceived the media coverage

as constructive. The community expressed great satisfaction that participants had received their results first.

3. *Closed Rehearsal of Community Presentation*—A full closed-door rehearsal presentation (summarized in the subsequent bullet) was presented by the study team to the CAC prior to the community meeting. The closed rehearsal ensured that the community meeting presentation was as inclusive and useful as possible.
    - *Lessons and Take-Away:* The CAC requested a presentation that was careful and simple to understand, incorporating a clear visual map so that residents could locate their residences with respect to the study results. During rehearsal, the CAC members provided feedback on the order of the agenda, comprehensibility of slides, choice of wordings to accord with terminology and usage in the area, structure of the presentation, and dealing with likely questions.
4. *Community Meeting*—The meeting commenced with “ground rules,” such as lawyers were not to solicit clients and questions were to follow the presentation. It was also communicated that continual stakeholder feedback is a success factor of the communication plan. In addition, representatives from the facility were invited to attend but were not permitted to present. The 45-minute presentation given by the study team detailed partnership objectives and study methods, results, and recommendations. A two-hour question and answer period followed the presentation. A summary of the study, recommendations (including the use of bottled water), sources of information, and how to access a study physician were distributed to all attendees on exit. The meeting summary and information on accessing free bottled water were mailed to households in the LHWA district and local authorities and representatives.
    - *Lessons and Takeaways:* The meeting proceeded in a constructive manner as CAC community members had predicted and not in the angry manner outside public relations experts had predicted. Any anger was directed at the responsible party and not at the investigators.
5. *Publication of Results and Information*—Following the community meeting, a newsletter with test result summaries was issued. A website with meeting presentation slides, test results, and FAQs was also developed. A summary of results was sent to all LHWA district residents.
    - *Lessons and Takeaways:* The website received many hits. The study and recommendations did not prove controversial. The practitioners did not encounter antagonistic relationships between the different parties.
6. *Availability to Answer Questions*—Physicians from the study team made themselves available to the public to answer questions from individuals and also from treating health care professionals.
    - *Lessons and Takeaways:* This service was appreciated. Questions mostly focused on the impact on residents with particular conditions such as liver and kidney disease. The many uncertainties surrounding the risk to humans were openly acknowledged.

15.4.1.4 Effectiveness of Communications

On the day results were presented and approximately 2 weeks after the initial press release, the responsible party announced that it would make free bottled water available to LHWA district residents (3 liters per day per person). Seventy-eight percent of eligible households accepted the offer.

Sixteen months after dissemination of the study results, a follow-up study of participants was made, which included repeat blood PFOA levels and questions about any changes in water usage. Sixty-five percent of those in the initial study participated in the follow-up, of whom 95 percent had made some change in their residential water usage in a way that would be expected to reduce PFOA intake. Eighty-eight percent had followed study recommendations to switch to using bottled water. The group median blood PFOA had declined 26%, consistent with a large effect for a pollutant with a half-life of approximately 4 years in humans.

USEPA used the results to enter into a consent agreement with DuPont to provide bottled water for the other impacted communities near the plant with >0.5 ppb of PFOA in water, and the states of Minnesota and New Jersey set provisional standards for PFOA levels in drinking water.

Lessons and Takeaways: The results and communications strategy resulted in 95% of participants had made a change to their water source. This response greatly exceeds the usual level of response seen with public health interventions. All parties, individuals, corporations, and governments acted in a prudent way with the disseminated information. Not all residents reacted by adopting the specific recommendations from the study; the alternate actions some individuals took are consistent with the information being incorporated into individuals’ own risk perceptions and with the development of a free market of solutions (individual decision making based on available information).

15.4.1.5 Case Study Summary

The Little Hocking Community-First Communication Strategy resulted in a great increase in alternate water source use by impacted community members and subsequently, a reduction in community PFOA blood levels. The success of the communication plan at the Little Hocking site was underlain by the four dimensions of risk communication:

- **Understanding:** Investigators worked with the community through the CAC to establish the communities' preferences and priorities in the form of a communication strategy and plan to maintain simplified and consistent messaging among stakeholder groups and interested parties, such as the media.
- **Perception:** Risk perception factors were incorporated into the outreach strategy, including residents' knowledge of PFOA biomonitoring results and associated illnesses, ability to access a physician, presence of vulnerable subpopulations (higher PFOA levels in children and the elderly), proximity of individual residences to elevated concentrations within the study area (sense of a safe place), and possible interactions of elevated PFOA levels and particular medical conditions.
- **Participation:** The affected community actively participated in all components of the communications.
- **Evaluation:** Success and effectiveness of the communication process were assessed based on feedback from the CAC, surveys of residents, and review of newspaper articles and other media content. In addition, a follow-up study was performed that addressed the effectiveness in terms of lowered blood levels of PFOA and a questionnaire about whether and how community members had changed their drinking water source as a result of the risk communication strategy.

15.4.2 State-Led Community Involvement Case Studies

The Environmental Council of the States (ECOS), in collaboration with the USEPA Office of Research and Development and the Association of State and Territorial Health Professionals, has developed a series of case studies presenting how state regulatory agencies are performing risk communication to PFAS-impacted stakeholders: https://www.ecos.org/documents/state-level-risk-communication-of-pfas-and-habs/

15.4.3 Washington County, MN: A State's Approach to Risk Communication

Washington County is home to 3M's Cottage Grove manufacturing facility as well as several disposal facilities where PFAS had been routinely disposed. Beginning in 2002, the State of Minnesota pursued drinking water investigations at the 3M facility and later near 3M's waste disposal sites in Washington County. According to the 2010 US Census, the population of Washington County, Minnesota was about 238,136, with the majority being Caucasian and between the ages of 18 and 64. Over 1,800 private wells, four major aquifers, eight municipal water supply systems, and over 150 square miles of groundwater were affected by the contamination. This impacted the drinking water supply of over 140,000 residents. After they were determined as the responsible party, 3M remained involved in the remediation efforts and paid for the majority of sampling throughout the county in coordination with MPCA.

This case study is discussed in the context of the risk communication plan.

15.4.3.1 Identify the Issue

The most widespread PFAS compound found in the region is PFBA. Additional prominent compounds include PFOS, PFOA, PFHxS. PFPeA, PFHxA, and PFBS which were always present as a mixture. When investigations began in 2002, there were many challenges to determining the impact for people as the science was in the very beginning stages of development. Therefore, MDH developed health-based guidance for PFOA and PFOS and the MDH lab developed the method to analyze water sample for PFOA and PFOS. As the science has progressed, MDH continues to update methods and health-based guidance.

Site communications are organized and performed in collaboration primarily between the Minnesota Department of Health and the Minnesota Pollution Control agencies. However, as with other PFAS sites, the site covers multiple local, county and state entities. Communications frequently entail only one or a few cities rather than the entire site. They may also need to be coordinated through all the cities and the county. This leads to multiple plans with multiple partners that are specific to an issue or communications plans developed for a specific project. The fundamental traits of successful risk communication over time and with all stakeholders for MDH include: empathy, care, competence, expertise, honesty, dedication, and commitment.

15.4.3.2 Set Goals

General communication goals and objectives for the site:

- Goal: Inform people about potential hazards to their person, property, or community and help them to make informed decisions about risks to their health.
    - Objective: Develop approved message blocks for PFAS topics and house in accessible format to encourage consistent information is used for all materials developed.
    - Objective: Provide regular updates about remediation activities at stakeholder group meetings including agency PFAS training meetings, county workgroup meetings, city council meetings and public meetings
    - Objective: Provide regular updates about health risks as scientific information changes/evolves at stakeholder group meetings including agency PFAS training meetings, county workgroup meetings, city council meetings and public meetings
- Goal: Encourage people to take precautions to reduce exposure to PFAS
    - Objective: Homes with contaminated drinking water are issued drinking water advisories and either connected to the city water or supplied with GAC filters that are maintained by the state.
    - Objective: Keep updated information about actions people can take to lower their exposure to PFAS on MDH website and MPCA website.
    - Objective: Mobilize stakeholder groups in the county or local communities to encourage people in their area to participate in remediation activities and processes offered by MPCA and contractors.
- Goal: Provide background information and present risks in an understandable way, using plain-language messaging.
    - Objective: Provide opportunities for people impacted by contamination to connect with appropriate staff to find information and to ask questions if concerned.
    - Objective: User test materials using MDH Plain Language Workgroup
- Goal: Bring new information as soon as available to build trust

Objective: Provide public meetings with open house sessions before and after a main presentation to bring new information to community

Objective: Provide availability sessions to encourage concerned people impacted by changes to learn more about their individual situations.

Project specific communications goals example:

Since 2002, there have been multiple changes in PFAS health based values provided by MDH, analytical advances which have impacted lab results, an investigation that looked at PFAS in garden produce and dust, multiple biomonitoring studies, fish monitoring and consumption guidance, drinking water and source water investigations, and a study to test point-of-use water treatment devices. All of these projects and scientific advances have resulted in specific communications to affected communities with goals and objectives tailored to the issue or project.

15.4.3.3 Identify Communities and Constraints

MDH catered their risk communication strategy to the following:

- Residents of affected communities
- Local governments: cities, townships, and their staff of varying sizes
- Washington County public health and environmental staff
- Legislators
- Other state agencies including MPCA

Constraints include the size of the area and the multiple local governments. The character of each township and city vary widely with different capacities to manage local information dissemination to affected residents. This requires communicators to develop relationships with each stakeholder group. The risks and impacts of PFAS contamination are managed differently for those on public water and private wells. Therefore, the correct information needs to be available in many different forms for different stakeholders.

15.4.3.4 Community and Stakeholder Assessment

Minnesota’s risk communication strategy in response to the Washington County PFAS drinking water contamination has been centered around community engagement and forging strong relationships with community members. Building these relationships enabled them to build trust with the community and develop new communication channels.

The Minnesota Department of Health (MDH), in conjunction with the Minnesota Pollution Control Agency (MPCA), maintains a hands-on risk communication approach. Information about community needs for information is gathered through regular update meetings with stakeholder groups and local government leaders. Public meetings, availability sessions and face to face interactions with community members during remediation activities provides a base of information for the ongoing communication efforts. MDH also maintains a 24/7 email and phone line for people to access with concerns or for information about site activities.

Minnesota had been engaging directly with affected communities since 2002. Having had a long-standing relationship with affected communities, MDH has a history of responding to the specific needs of the affected communities and has tailored its messaging to their knowledge level. Although basic information about PFAS is always available, the general level of knowledge amongst key stakeholders is high. For this reason and with these communities, MDH representatives lead with high-level information, as the attendees to the public meetings typically are interested in specific updates as opposed to rudimentary background information.

15.4.3.5 Identify Messages

MDH maintains a message block document with approved message blocks about a variety of topics for internal staff use. This document serves as the basis for specific information sheets developed for different stakeholder activities. It is also a resource to answer questions from concerned community members. Topics include health risk of PFAS, MDH guidance value information, current site activities, exposure information, fish consumption guidance, swimming, cumulative health risk, breastfeeding and health risks, PFAS and links to health problems, testing blood for PFAS, biomonitoring information, gardening and PFAS, and results of MN Cancer Surveillance System reports.

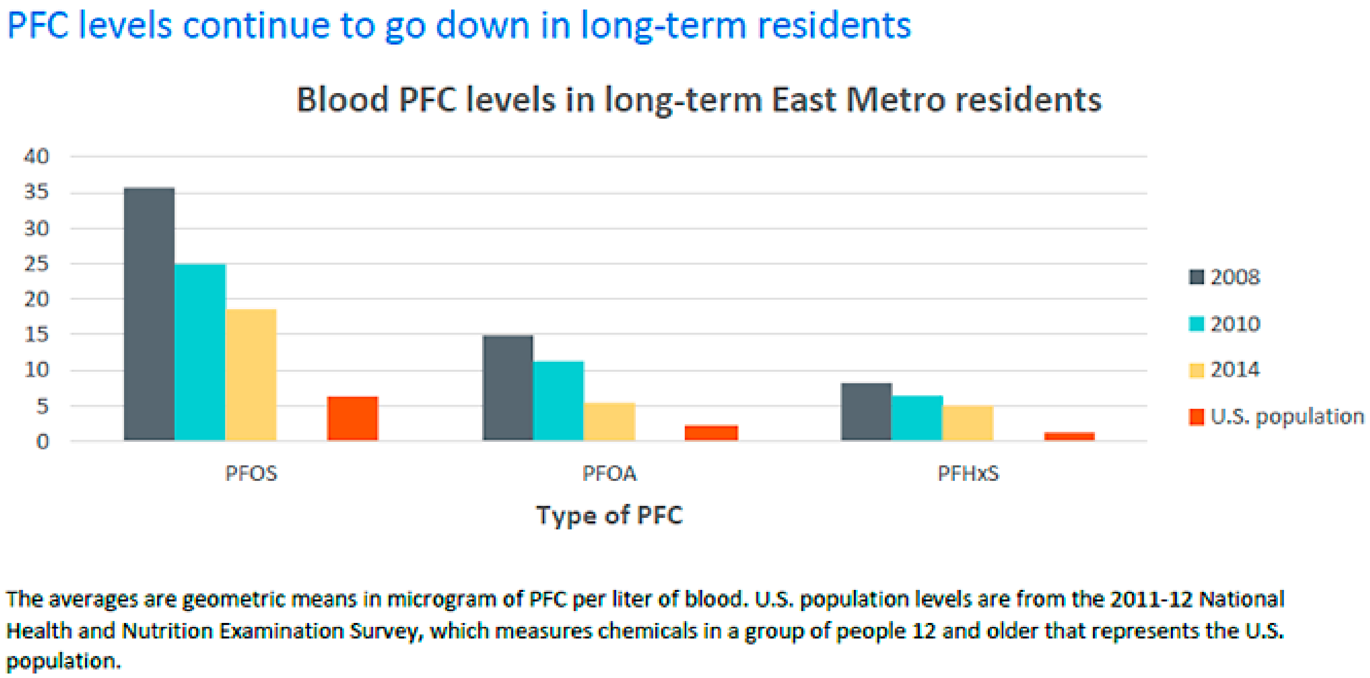
MDH notes the importance of discussing the scientific method with stakeholders to remain transparent about their course of action. They also share new knowledge as it becomes available and do not wait until they have a perfect message or until they know all of the facts to engage with the community. In an effort to uphold their principle of transparency, MDH acknowledges points of uncertainty and are clear about what they do not know when communicating with the public.

The messages are presented in different ways to different communities depending on the level of understanding that a community has about PFAS. For example, we had several meetings in 2018 for communities. One meeting was to a community which had not had PFAS contamination issues until 2018. The information for this community was presented in more of an elementary, broad overview style and level. Another presentation in the same month was to a neighboring community that had been involved with PFAS contamination since 2002. The presentation focused more on what the new information was rather than PFAS basics as the community had a more developed understanding of PFAS.

Examples of specific messages:

- Testing is available for households on private wells that would like their drinking water tested for PFAS. If test results show elevated levels, options are available from the MPCA for treating the water and reducing exposures.
- Currently, PFAS levels found in the drinking water supply in impacted communities have been within the margin of safety for the current drinking water guidance values, and outright negative health effects from these exposures are not expected with what is currently known about PFAS exposures and health effects.
- Affected water supplies are safe to use to water produce in home gardens.
- Biomonitoring Data Shows Interventions are working

Figure 15-24 includes biomonitoring data for three PFAS compounds over the time period from 2008 to 2012. This study shows that although we can’t answer questions about health effects, we can demonstrate the work we are doing to reduce exposures has paid off.



PFC levels continue to go down in long-term residents

The averages are geometric means in microgram of PFC per liter of blood. U.S. population levels are from the 2011-12 National Health and Nutrition Examination Survey, which measures chemicals in a group of people 12 and older that represents the U.S. population.

Figure 15-24. **Biomonitoring Data**

Source: Courtesy of the Minnesota Department of Health

- Because of the extreme persistence and mobility of these compounds, a PFAS megaplume developed which is much larger than early modeling predicted. One of the primary factors in this was the unanticipated transport of PFAS via surface water and then re-infiltration to groundwater far away from the source areas – a transport pathway not typically seen in persistent environmental contaminants, which tend to adsorb to organic carbon in soils and sediments.

15.4.3.6 Select Communication and Engagement Tools

MDH's risk communication strategy facilitates community engagement and open dialogue.

- Engaging with stakeholders and communities as soon as possible when there is any change in risk management of PFAS. Builds trust over time that MDH will be there to support and help communities.
- MDH sends the right people/experts/staff to deliver messages. Over time, staff have built relationships with stakeholders.
- When interacting with people impacted by the site, staff stays until all questions are answered – whether it is a phone call, a public meeting or availability session
- MDH has a service-oriented approach to community engagement. They recognize that educating the community members will carry a ripple effect. Attendees from the meetings who learn through the presentations and the open house format will then take the information and share it with other members of the community.

MDH used the following strategies to connect with and inform the affected communities:

- Hosting Public Meetings: Public meetings have been a significant part of community engagement in Washington County. MDH has held public meetings in an open house, presentation, and Q&A format. An open house is followed by a presentation given to the attendees, after which they provide a time for questions and answers, followed by additional open house time. Participants are able to ask questions about their particular situations in an open forum setting or in one-to-one conversations. For example, in Spring 2017, MDH in collaboration with MPCA held two presentations in different areas of Washington County. The city of Cottage Grove meeting attracted 130 people. In Lake Elmo, a region where the majority of residents have private wells, approximately 120 people attended the public meeting.
- Hosting Availability Sessions/Office Hours: MDH organized opportunities to provide people with time to interact with staff one on one and ask questions. Typically, MDH held these events after major sampling events happened or when new or updated information was released. MDH extended these opportunities upon request of the community. The events were widely used. In an event held in Fall 2017, the office hours held in Lake Elmo where the majority of residents have private wells attracted 45 people. With the affected area being so large,

personal communication was helpful in establishing relationships with members of the community.

- Providing Online Resources: The MDH website outlined the history of PFAS in Minnesota as well as actions they have taken and health-based guidance information. An electronic online sampling request form was available on the MDH website. An electronic map on the website shows where MDH is sampling and community members could see and check their property's location in relation to the PFAS contaminated sites. MDH also had a widely used email address for residents to ask questions directly to the department. They could also subscribe to the government's delivery email list to get new information directly to their inbox.
- Communicating with Local Government: MDH prioritized communication with local government because it was a useful tool in keeping the communities informed. They visited city councils to provide updates on the PFAS investigations. They also provided technical support to local governments and their staff that were responsible for protecting public drinking water.
- Using the Media: MDH used press releases and interviews to disseminate information. Social media became a useful tool as well.

15.4.3.7 Implement Strategy

Strategies implemented included:

- Drinking Water Advisories: Over 2700 private wells have been sampled in the East Metro and over 1, 100 drinking water advisories have been issued. Homes that have been issued drinking water advisories are either connected to city water or provided bottled water and/or GAC filters maintained by the state. MDH and MPCA collaborated to communicate and coordinate action for this work.
- Public Water Systems: There are five community public water supplies in the East Metro that have individual wells above the MDH health-based guidance values. All of these cities put in place interim measures to manage their public water supply systems to provide drinking water at or below the MDH health-based guidance values. MDH collaborated with these communities to provide information to residents.
- Messages to Community: After developing health-based guidance values for PFAS compounds, MDH sought to explain to the community what these values mean and what concerns they address. They also explained the next steps in their action plan.
- Reiterating Commitment: MDH drives home the message that they are committed to bringing updated information to the communities to inform them of the status of their efforts. This assures the community that MDH is determined to support them and address their concerns.
- Collaboration with Other Stakeholders: MDH collaborated with MPCA on a response to the PFAS contamination. Any message that were released to the public by MDH was in conjunction with MPCA. ATSDR also developed a community engagement book which has guided MDH's risk communication strategy. Additionally, MDH worked closely with city administrators and community leaders to keep them informed prior to the public meetings.
- Concessions: When drinking water levels were found to be above guidance values in private wells, bottled water was provided by MPCA until a GAC system can be installed.

15.4.3.8 Evaluate, Debrief and Follow Up

Continuous improvement of risk communications and activities through evaluation and through providing feedback loops with stakeholders supports the ongoing implementation strategies described above. The sampling and remediation activities have been widely successful in part due to the community engagement and communications efforts that have built trust in the community for the state agencies.

Evaluation methods used to understand effectiveness of communications content and process include one on one surveys at events, hot washes with partner agencies after communications efforts, and feedback from community leaders at regular update meetings.

Continuously improving, refining, and developing materials to meet community concerns and needs that are identified by inquiries or contacts staff have with community members. Contacts are primarily through 24/7 email and phone line as well as in person while in the field or at public events.

Materials have been developed in many formats over the years and have changed due to capacity for communities to use various methods and MDH capacity to produce them – video, face to face meetings, print, social media in coordination with partners. Investigations and other information have also resulted from community concerns. These include Cancer Incidence Reports, home and garden study, site-specific meal advice for fish consumption, point-of-use filter testing, clinician information sheet, and an information sheet about testing blood for PFAS.

15.4.3.9 Successful Outcomes

The Minnesota Department of Health has been very successful in community engagement:

- They have earned the trust of the community, and residents are assured that MDH is working hard to solve the issue at hand. The number of people participating in sampling and remediation speaks to the efforts made to connect with affected people. Exit surveys from public events have shown that people feel staff are working hard and are good at the work they do.
- MDH also has invested their resources in research and has made strides in understanding the health impacts of the PFAS contamination their state is facing. Many of the investigations and projects were in response to concerns collected through contacts with community members and leaders. These include Cancer Incidence Reports, home and garden study, site specific meal advice for fish consumption, point-of-use filter testing, clinician information sheet, and an information sheet about testing blood for PFAS.
- They have used biomonitoring to demonstrate that their efforts have reduced the PFAS levels in people's bodies. This has provided the community with tangible evidence that the work they are doing is making a difference.

15.4.3.10 Lessons Learned

- It is vital to be on the ground and engage with the community face-to-face. This helps build trusting relationships with the community which has facilitated the remediation efforts and supported reducing exposures to PFAS for community members.
- The cross-agency effort to address the PFAS concerns in Minnesota is a challenge and takes effort to coordinate, but over time has been an effective strategy to address exposures to PFAS in a timely manner.
- Dealing with residential homes and homeowners can be complex. Because PFAS is a complex emerging contaminant for which research and information is constantly evolving, it can be a challenging to return to residents with new guidance values based on new health risks. The information has to fit for those who are familiar with PFAS and those who are new homeowners or residents in affected communities.
- It is important to learn what information residents are looking for and relay it in an articulate manner and in a way that is useful to them. Another concern Minnesota residents have had is a potential decline in property value, but this concern has faded with time.
- Additionally, it is important to be understanding and sympathetic toward the affected residents when they are upset. They are concerned for the well-being of their families.

15.4.3.11 Better Practices Moving Forward

Moving forward, MDH notes that sites across the state have similar circumstances and similar concerns. The lessons learned from sites they have already worked with have been beneficial in refining their approach with other affected communities and contaminants. They have had success with duplicating their strategies and methods at other sites. Although the general principles have been effective, every community is slightly different. MDH takes the time to understand the dynamics of each particular community and tailor their risk communication methods accordingly.

15.5 Surface Water Quality Case Studies

15.5.1 PFAS-Containing Foam

Case Study: Minnesota Project 1007 Feasibility Study (Contributed by Rebecca Higgins, MPCA)

15.5.1.1 Issue

The surfactant and micelle properties of per- and polyfluoroalkyl substances (PFAS) have proven to result in accumulation into foams on surface waters in many states. The observed foam has implications for exposure to people, aquatic life, wading and dabbling birds, and other wildlife. The concentrations of PFAS in these foams are documented to be thousands to millions of times higher than the concentrations in the water column.

15.5.1.2 Background

In May 2019, the Minnesota Department of Transportation (MNDOT) requested water sampling from the Minnesota Department of Health (MDH) within the area of a transit project in the East Metro of the Twin Cities Metropolitan Area (TCMA), potentially in an area of known PFAS contamination. In response, the MDH sampled surface water and foam above the surface water of Battle Creek located downstream from the area of interest for PFAS. At that time, analytical results indicated PFOS and PFOA impacts were present in the surface water at concentrations of 0.013 ppb and 0.017 ppb, respectively. Comparatively, PFOS and PFOA were present in the foam at 140,000 ppt and 11,000 ppt, respectively, indicating an enrichment compared to the paired surface water results.

In 2020, this occurrence of PFAS-containing foam led the Minnesota Pollution Control Agency (MPCA) to look for its presence as part of the Project 1007 Feasibility Study also in the East Metro under the 2018 3M settlement. Project 1007 conduit drains surface water across the northern portion of the east metropolitan area of the Twin Cities. Foam was noted on the surface of Raleigh Creek and in the corridor from the closed 3M Oakdale Disposal Site, and past the confluence of Raleigh Creek with the Project 1007 stormwater conduit (Figure 15-25). The foam was located on the flowing creek, stormwater ponds, and Lake Elmo. The foam was noted particularly after rain and wind events that occurred during the weeks of surface water and sediment sampling.

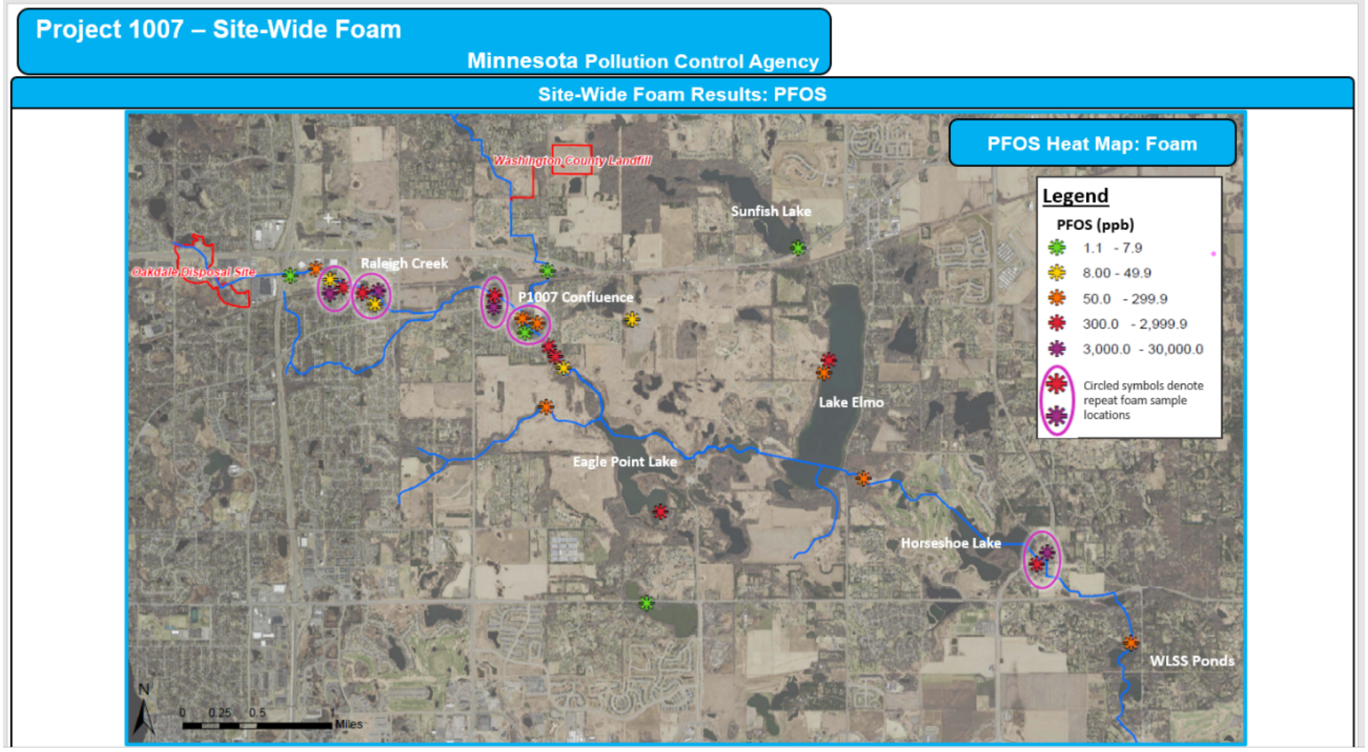


Figure 15-25. Heat map of PFAS-containing foam detections throughout Project 1007 study area.
Source: Project 1007 Minnesota Pollution Control Agency (MPCA 2023)..

The foam has been collected throughout the feasibility study from surface water across the Project 1007 corridor in accordance with the Michigan PFAS Action Response Team (MPART) protocols (MI EGLE 2019). Following collection, the foam is allowed to condense in the PFAS-free baggie before being sent to AXYS SGS laboratory in Canada for analysis of up to 40 PFAS compounds. The foam samples are screened for potential high concentrations prior to analysis by AXYS SGS method MLA 110, which aids the laboratory in understanding the potential variation in foam concentrations prior to analysis.

15.5.1.3 PFAS-Containing Foam Varied Textures or Type

PFAS-containing foam can have several different appearances across the Project 1007 region. Specific types of foam were not tied to an exact location, precipitation events, or seasons apart from frozen foam. Examples of different foam types are shown in Figure 15-26.

At three locations in Project 1007 (RC5, RC7, and RC12) in 2020, foam was collected and analyzed for PFAS twice to assess potential variation in PFAS concentrations depending on foam type. At each location, a “fluffy” foam sample was collected for comparison against a “thin” foam. PFOS concentrations from the larger and fluffier piles of foam were between two and three orders of magnitude greater than their thinner counterparts. The corresponding surface water samples had negligible variation in PFOS, suggesting that the PFAS enrichment in foam can be highly variable due to the environmental conditions.

Generic Foam Type	Description	Sampling Location Photo
Actively Generating and Reaccumulating	Foam is observed floating upstream of the accumulation point and continuing to actively accumulate at a location. Frequently source of generation is apparent, and foam will reaccumulate rapidly after sample collection. This foam can either accumulate in large quantities in singular locations or across a wide stretch of creek bank.	RC18A (5/5/20) 
Deflated (old)	Foam is typically thin, in smaller quantities, and discolored with organic matter present. Further, no foam is observed upstream or downstream of point of accumulation, and source of generation is not obvious. This foam is thought to be old because it has never been observed to be actively generating.	RC7 (8/12/2019) 
Frozen	Foam appears frozen, often has a different color and texture from surrounding snow and ice and is usually thin.	RC7A, 2/24/2020  EP19 2/25/20 

Figure 15-26. Examples of various PFAS-containing foam observations and characteristics.
Source: Project 1007 Six-Month Investigation Progress Report, Minnesota Pollution Control Agency, October 13, 2020 (MPCA 2020)..

15.5.1.4 Formation and Accumulation

The requirements for PFAS-containing foam to form and accumulate are typically:

1. Turbulence—Air must be mixed into the water column for foam to form. This can be caused by water flowing

over rocks, trees, or other debris in the stream. The water level greatly affects the locations of turbulence.

2. Solid substrate—After formation, the foam bubbles must have a solid substrate in relatively calmer water to accumulate along or against. Without accumulation, the foam bubbles will collapse back into the stream water column. Foam can be found to accumulate along the stream banks, debris, blocks of ice, and vegetation growing in the stream channel.
3. PFAS concentrations in surface water—Foam may naturally form regardless of the presence of PFAS. It is also not well understood how much PFAS will preferentially separate (enrich) into the foam relative to the PFAS in the corresponding surface water.

These and other factors affect the ability to predict occurrence and remediation of PFAS-containing foam. PFAS-containing foam has been encountered in surface water at the same order of magnitude (approximately 20 ppm) at a source area (Oakdale Disposal Site) and approximately 8 miles downgradient in the connected drainage system. Large masses of PFAS-containing foam have been visually noted to dissociate small portions of bubbles off from the larger mass, travelling downstream and potentially providing an additional PFAS source to the water bodies and/or sediments downstream. PFAS-containing foam has been observed to be intermittently present, as it may form and then dissolve back into the water column in a matter of minutes. This may impede response actions to removing the foam; reports of foam in known PFAS-impacted waters may not be present by the time a response action is attempted or it may form elsewhere in the surface water system.

15.5.1.5 PFAS-Containing Foam Enrichment Factors and Carbon Chain Length

An enrichment factor is the ratio of the PFAS concentration in the foam to that in the water (usually the top 6 inches of the water column). As shown in Figure 15-27, the enrichment factors for PFOS in the Project 1007 region varied by over an order of magnitude, supporting the environmental factors previously described as important to PFAS enrichment in foam in addition to PFOS concentrations in the corresponding surface water. The relative importance of environmental conditions that may influence PFAS enrichment are not well understood at this time.

Foam samples overwhelmingly consisted of long-chain PFSAs and PFCAs constituting up to 97% of the PFAS compounds in some samples (Figure 15-28). Longer chain PFAS like PFOA, PFOSA, PFOS, and N-EtFOSA tend to enrich or preferentially separate into the foam to a greater degree than shorter chain compounds like PFBA and PFBS because they are more hydrophobic.

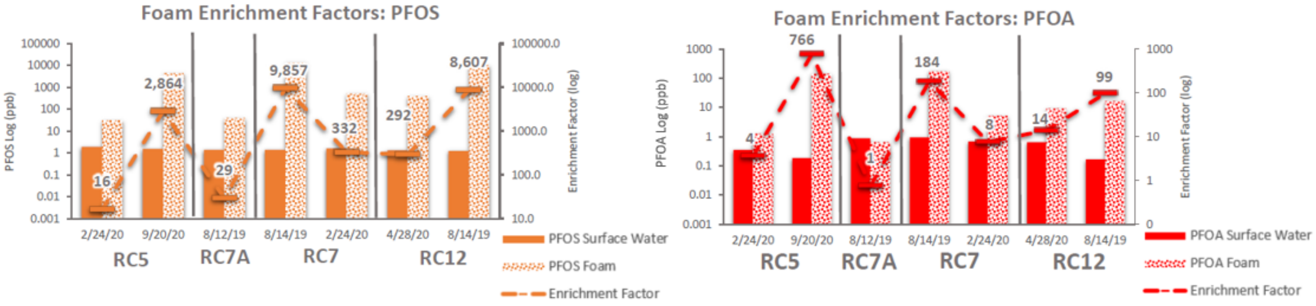


Figure 15-27. Foam enrichment factors for paired surface water and foam samples, showing PFOS and PFOA concentrations.

Source: Project 1007 Minnesota Pollution Control Agency (MPCA 2023)..

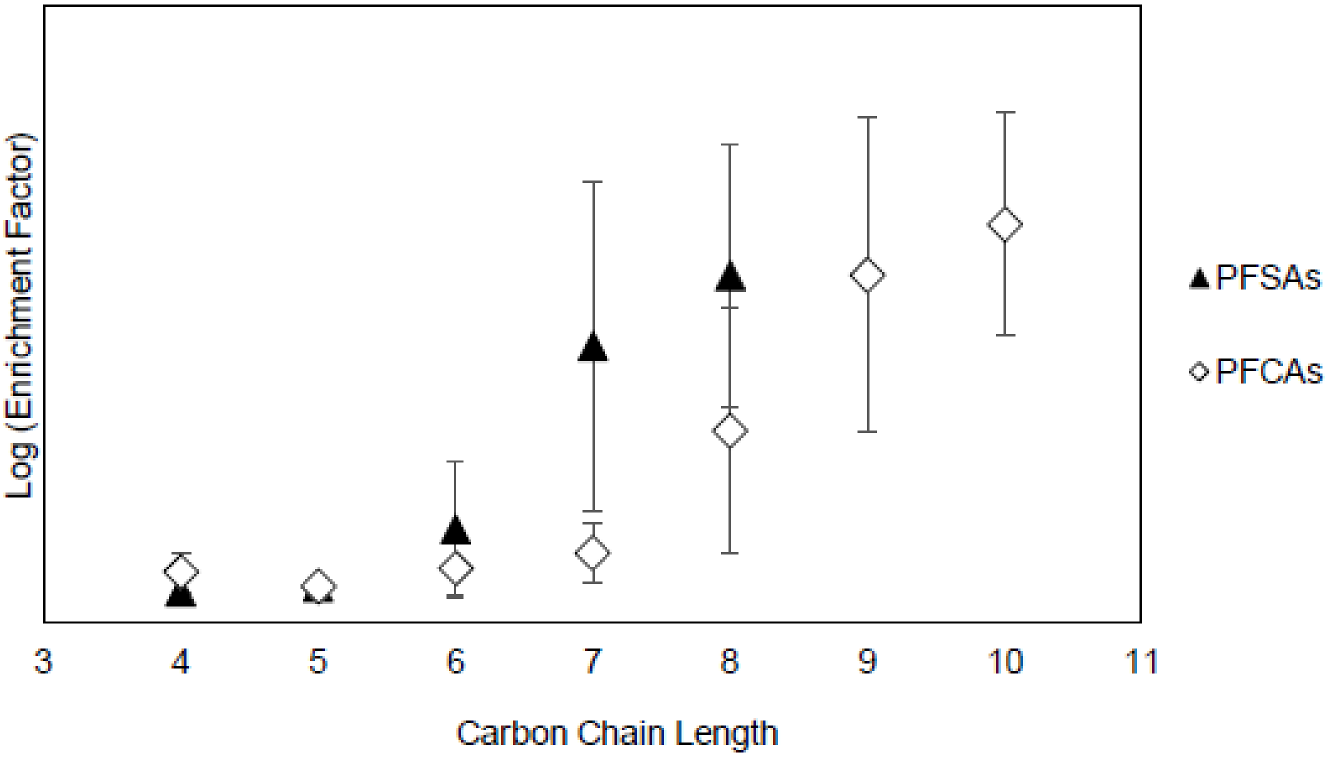


Figure 15-28. PFAS-containing foam enrichment factors and carbon chain length versus enrichment factors.
Source: Six-Month Investigation Progress Report (November 11, 2019—May 15, 2020) Project 1007 Minnesota Pollution Control Agency (MPCA 2020).

15.5.1.6 Risk Assessment

Risk assessments for PFAS are limited by lack of sufficient toxicological and exposure data for all but a few chemicals such as PFOS and PFOA. Therefore, to ensure protection to people and their pets who contact surface waters with PFAS-containing foams, the public needs to be broadly informed to avoid contact with any foam. Naturally occurring foams can also harbor bacteria and viruses. In areas with known PFAS contamination, targeted risk messages and outreach have also occurred. According to the State of Michigan (MI DHHS 2019), incidental ingestion and extended, recurring, whole-body contact with PFAS-containing foam can result in a public health hazard for children and adults. Where PFAS-containing foam exists, the Michigan Department of Health and Human Services (MDHHS) recommends a health advisory to avoid the incidental ingestion of and whole-body contact with the foam as a precaution.

According to the Minnesota Department of Health (MDH), “PFAS-containing foam on surface water does not pose a risk to human health if skin contact with foam is minor and infrequent” MPCA 2020. MDH recommends informing people of observable foams in the PFAS-contaminated areas where concentrated PFAS could be encountered. Additionally, “MDH recommends:

- People and pets should avoid contact with foam on surface waters in this area.
- Wash skin that has come into contact with PFAS-containing foam with soap and water” MPCA 2020.

Other states, such as Wisconsin, provide a reporting system for suspected PFAS-containing foam across the state, and provide health advice to avoid the foam (WI DNR 2022).

More research is needed to determine how to estimate exposure to people, especially children; pets; aquatic organisms; water birds; and wildlife.

There are limitations on how to account for exposure estimates from foam concentrations, as well as the best way to sample for foam. Because the PFAS-containing foams form at the air-water interface, there are risks for higher exposure to swimmers, dabbling ducks, aquatic insects, etc., that are not accounted for with only collecting water column samples. Broad outreach to avoid any surface water foam is still not occurring.

In addition to outreach and messaging, using authorities from remediation or Clean Water Act regulations is critical for making progress on reducing the risks of PFAS to people and ecological species. Most states and tribes have narrative standards in their water quality standards that prohibit nuisance conditions on surface waters. These could be applied to restrict sources causing PFAS-containing foams.

15.5.1.7 Take-Aways for PFAS-Containing Foam

Based on this case study, the following takeaways with respect to PFAS-containing foam are:

- Foam occurs on surface water bodies naturally but may contain PFAS compounds when located near a source of PFAS releases. The PFAS-containing foam may look like naturally occurring foam.
- The foam occurs more frequently during precipitation and wind events. The foam appears to be a concentrated form of PFAS compounds, at higher levels than PFAS occurring in the surface water below the foam.
- Based on data collected to date, the predominant forms of PFAS in the foam are the longer chain compounds such as PFOS, PFOA, PFOSA, and N-EtFOSA rather than the shorter chain compounds such as PFBA and PFBS.
- PFAS-containing foam has been found in multiple waters in the Twin Cities East Metro, including waters that border parks and residential areas such as Raleigh Creek and stormwater ponds in Oakdale (including Tablyn Park) and the city of Lake Elmo. PFAS-containing foam has also been found on Battle Creek in Battle Creek Regional Park in St. Paul. This has resulted in the need for institutional controls for new developments and specific outreach by letter to residents.
- The best risk assessment advice is to avoid any surface water foam, because even naturally occurring foam can carry microbial risk to people or pets contacting it.

What PFAS-Containing Foam Is Not

- Not all foam on surface water bodies contains PFAS.
- Where PFAS-impacted surface water exists, PFAS-containing foam may not always be present, as it occurs more frequently with precipitation and wind events.
- PFAS-containing foam may not be removable in all circumstances and may re-occur in locations where it has been previously removed.

More information on Project 1007 is located on the MPCA website (MPCA 2023).

15.5.2 Surface Water/Groundwater Interaction Case Study

As mentioned in Sections 16.4.5, 5.3.4, and 10.3.1.2, surface water/groundwater interaction may play a role in a conceptual site model and locating places to sample. This case study provides three examples where this interaction can impact surface water quality.

15.5.2.1 North Carolina Example

The first example is found in the dialogue box in Section 16.6.4.1 and looks at PFAS in groundwater impacting surface water. A surface water body in North Carolina was found to have unacceptable concentrations of PFAS. An adjacent industrial facility had caused the groundwater to be contaminated with the same PFAS. An investigation of the groundwater showed that it is discharging to the surface water and contributing approximately 60% of the PFAS load to the surface water. A portion of the remedy for the site included groundwater extraction, treatment, and discharge to reduce the mass flux of PFAS in groundwater to the receiving surface water (NC DWR 2022).

15.5.2.2 Minnesota Examples

The second example is from Minnesota and provides a case study of PFAS-contaminated groundwater impacting surface water and PFAS-contaminated surface water impacting groundwater. These processes have significantly contributed to a 150-square-mile PFAS plume in groundwater that has impacted eight municipal water systems and 2,700 individual private water supply wells in Washington County, east of St. Paul. Wastes containing high PFAS concentrations originating at a manufacturing facility were disposed in two off-site landfills and several burial pits at the industrial facility. PFAS contamination in groundwater was found downgradient from the two landfills. Additional locations of groundwater containing PFAS were found in areas that were not expected based on groundwater flow directions (westerly and southwesterly) at the landfills.

As it turns out, surface water emanating from wetlands around one landfill carried PFAS to the east where it infiltrated to groundwater 1 mile downstream. This groundwater resurfaced as surface water and flowed to the east in a system of creeks, ditches, and pipelines that entered several lakes and ponds. Stormwater runoff was conveyed by the same conveyance system providing additional transport of PFAS to the east. The surface water transport and the exfiltration from the conveyance features and lakes/ponds resulted in PFAS in groundwater along the surface water path and downgradient from the lakes. The PFAS contamination along this route was enhanced by the discharge of extracted groundwater containing PFAS and other pollutants adjacent the second landfill to the same stormwater conveyance system discussed above over a period of 7 years. This conveyance system terminates at the St. Croix River 6 miles downstream from the first landfill. Thus, at this site there is PFAS in groundwater, daylighting as a surface water and then re-entering groundwater as the water is transported downstream and temporarily resides in various lakes and pond. This results in exposure through use of the groundwater for municipal purposes and use of the surface waters for municipal purposes, fishing, recreation, and wildlife habitat. (Regenesis 2019).

The third example is from Minnesota and is a subset of the second example. In one location overlying the 150-square-mile groundwater PFAS plume is a site where several different mixtures of AFFF were used to put out a fire at a plastics manufacturer. The runoff from the fire suppression went down a ditch to a small surface water body. Migration of surface water to groundwater at that location resulted in contamination of groundwater by PFAS impacting several private water supply wells that were completed on the order of 250 feet in depth. Sampling showed that the less mobile, longer chained PFAS PFOS and PFHxS had the highest concentrations in the sediments along the ditch. The sediments at the surface water body still contained those two PFAS, but not at as high of a proportion relative to the more mobile, shorter chained PFAS PFOA and PFBA as found along the ditch. The water in the surface impoundment had substantially more PFOA and PFBA than PFOS and PFHxS. This shows not only the transport of PFAS in surface water to groundwater, but the changing composition of PFAS in the surface water due to varying portioning properties of PFAS.

15.5.2.3 Summary

These three examples demonstrate the need to assess the potential surface water/groundwater interactions when looking for sources of contamination, routes of exposure, and establishing a CSM. These examples show the potential for adverse impact, but do not provide an assessment of the potential change in PFAS constituents and concentrations that may occur during the movement of water from surface water to groundwater or groundwater to surface water. Those potential changes are associated with biotransformation that may occur due to water chemistry changes in the vicinity of the groundwater-surface water interface. A discussion of this issue is found in Section 5.3.4.2). An additional example of PFAS impacts from a groundwater/surface water interaction can be found in Section 5.3.4.

Updated September 2023.

16 Surface Water Quality

The purpose of this section is to support the PFAS Technical and Regulatory Guidance Document (PFAS Guidance Document) users (state and federal environmental staff, stakeholders, project managers, and decision makers) to gain a working knowledge of the current state of PFAS science and practice for surface water quality. The section does not include calculated criteria, rather it provides available information and references that can then be used to support development or review of criteria or guidance values to protect surface water quality.

Section Number	**Topic**
16.1	Introduction
16.2	Protection of Human Health
16.3	Protection of Biota
16.4	Sampling and Analysis
16.5	Surface Water Foam
16.6	Effluent Limits for PFAS
16.7	Surface Water/Groundwater Interaction

16.1 Introduction

This section provides information to help fill in the gaps related specifically to concerns with PFAS-impacted surface water and associated receptors. Several states have expressed a need for technical information to support the development of surface water quality criteria (WQC) or guidance values for uses other than drinking water, including but not limited to habitat for fish and other aquatic life. USEPA (2020) developed recommendations and provided derivation methods for surface water criteria “for determining when water has become unsafe for people and wildlife using the latest scientific knowledge.” States and tribal governments may, and sometimes do, develop their own numerical criteria. To protect human health, the states and tribal governments may also establish water body–specific fish consumption advisories for certain aquatic species. These advisories are recommendations and not enforceable. This section provides technical information regarding PFAS in surface water that individual states and tribal governments can consider when developing criteria according to their own processes and policies. This information focuses on two main issues. First is the protection of human health from a variety of potential exposures to PFAS in surface water, such as drinking water, consumption of fish and other aquatic species, and from recreational activities. Second is the protection of biota, based on available ecotoxicity data, bioaccumulation and concentration factors, and aquatic-dependent wildlife considerations, among others.

USEPA has published draft national recommended aquatic life criteria for PFOA and PFOS in freshwater for public comment (USEPA 2022, 2022) and a fact sheet for the criteria (USEPA 2022). In addition, USEPA had published their responses to external peer reviews of the draft criteria (USEPA 2022, 2022). USEPA has also issued two memoranda for National Pollution Discharge Elimination System (NPDES) permits and PFAS. One addresses PFAS under USEPA-issued NPDES permits for wastewater and stormwater discharges (USEPA 2022) and the other discusses PFAS in state-issued NPDES permits and pretreatment programs (USEPA 2022). As of the writing of this document, there are few formally established surface water criteria for any PFAS that are protective of uses of surface water other than as drinking water. Florida, Minnesota, and Michigan are examples of states that have aquatic life protection values (see the Water and Soil Regulatory and Guidance Values Table Excel file).

In addition to the well-established issues associated with PFAS in surface water, such as use of the surface water as a source of drinking water and accumulation of PFAS in biota, this section also includes a discussion of a relatively new issue related to surface water: PFAS-containing foam. Investigations in at least three states—Minnesota, Michigan, and Wisconsin—have found that concentrations of PFAS in surface water, or discharging to surface water, at sufficient levels can generate foam on surface water. That foam acts to remove PFAS from the water column, but also acts as a secondary source of PFAS as the foam leaves the surface water and is deposited in terrestrial or other aquatic locations.

16.1.1 Beneficial Uses

One of the first steps in developing the criteria is to determine the beneficial uses that are to be protected for the water body of concern. These have usually been developed by the state organization responsible for water quality and/or water resources for the state. That regulatory agency assesses potential beneficial uses and assigns appropriate designated uses for a water body. As examples, in Massachusetts this task is the responsibility of the Massachusetts Department of Environmental Protection, while in California it is under the purview of the nine Regional Water Quality Control Boards that establish potential beneficial and designated uses for the water bodies for each region. The process for establishing these beneficial uses in most instances follows protocol developed by USEPA (2020).

With the potential adverse health effects associated with the ingestion of certain levels of various PFAS, negative impacts on beneficial uses of surface water may occur. Table 16.1 provides a fairly comprehensive list of potential beneficial uses for surface water. This table is a compendium taken from the *Water Quality Control Plan (Basin Plan) for the California Regional Water Quality Control Board, Central Valley Region, Fourth Edition, Sacramento and San Joaquin River Basins* (RWQCB-CVR 2016). Different jurisdictions use different lists of beneficial uses. The list in Table 16-1 is used for illustration. For an evaluation of PFAS, the list may be substantially reduced in order to focus on those that are appropriate, as the presence of PFAS may not have an impact on a particular use (for example, navigation). In the table the list has been reduced by separating the beneficial uses that may be impacted by PFAS (light blue) and those that are not likely to be (light green). The list can be further reduced by combining several of the uses that evaluate similar issues, such as aquatic toxicity. As an example, the beneficial uses listed as WARM, COLD, EST, WILD, BIOL, and RARE (see Table 16.1) are each designed to protect aquatic species that have a range of attributes. The beneficial use for shellfish could be added to that grouping by expanding the evaluation under it to include benthic organisms and sediment quality.

Table 16-1. Beneficial Uses

Source: Adapted from RWQCB-CVR (2016)

	Beneficial Use	**Description**	**Does PFAS Have Impact on Use? Covered in this Section**
1.	Municipal and Domestic Supply, Use as Drinking Water (MUN)	Uses of water for community, military, or individual water supply systems, including, but not limited to, drinking water supply.	Yes
2.	Agricultural Supply (AGR)	Uses of water for farming, horticulture, dairy operations, or ranching.	Yes
3.	Primary Water Contact Recreation (REC-1)	Uses of water for recreational activities involving body contact with water, where ingestion of water is reasonably possible.	Yes
4.	Groundwater Recharge (GWR)	Uses of water for natural or artificial recharge of groundwater.	Yes
5.	Commercial and Sport Fishing (COMM)	Uses of water for commercial or recreational collection of fish, shellfish, or other organisms.	Yes
6.	Aquaculture (AQUA)	Uses of water for aquaculture or mariculture operations.	Yes—not all components covered under other beneficial uses—harvesting of aquatic plants for human consumption
7.	Warm Freshwater Habitat (WARM)	Uses of water that support warm water ecosystems.	Yes—combine with COLD
8.	Cold Freshwater Habitat (COLD)	Uses of water that support cold water ecosystems.	Yes—combine with WARM

	Beneficial Use	**Description**	**Does PFAS Have Impact on Use? Covered in this Section**
9.	Estuarine and Marine Habitats (EST)	Uses of water that support estuarine and marine ecosystems.	Yes—combine with WARM and COLD for ecotoxicity for all of the aquatic species
10.	Wildlife Habitat (WILD)	Uses of water that support terrestrial or wetland ecosystems.	Yes—food chain issues, in addition to WARM, COLD, and EST
11.	Spawning, Reproduction, and/or Early Development (SPWN)	Uses of water that support high quality aquatic habitats suitable for reproduction and early development of fish.	Yes
12.	Shellfish Harvesting (SHELL)	Uses of water that support habitats suitable for the collection of filter-feeding shellfish.	Yes
13.	Hydropower Generation (POW)	Uses of water for hydropower generation.	No—PFAS not expected to impact POW
14.	Industrial Process Supply (PRO)	Uses of water for industrial activities that depend primarily on water quality.	No—as below for IND
15.	Freshwater Replenishment (FRSH)	Uses of water for natural or artificial maintenance of surface water quantity or quality.	No—issues covered under other beneficial uses
16.	Non-contact Water/Secondary Contact Water Recreation (REC-2)	Uses of water for recreational activities involving proximity to water, but where there is generally no body contact with water, nor any likelihood of ingestion of water.	No
17.	Preservation of Biological Habitats of Special Significance (BIOL)	Uses of water that support designated areas or habitats, such as established refuges, parks, sanctuaries, ecological reserves, or Areas of Special Biological Significance, where the preservation or enhancement of natural resources requires special protection.	Not covered individually—covered under WARM, COLD, EST, and WILD
18.	Rare, Threatened, or Endangered Species (RARE)	Uses of water that support aquatic habitats necessary, at least in part, for the survival and successful maintenance of plant or animal species established under state or federal law as rare, threatened, or endangered.	Not covered individually—covered under WARM, COLD, EST, and WILD
19.	Migration of Aquatic Organisms (MIGR)	Uses of water that support habitats necessary for migration or other temporary activities by aquatic organisms, such as anadromous fish.	No—issues already covered under other beneficial uses
20.	Industrial Service Supply (IND)	Uses of water for industrial activities that do not depend primarily on water quality, such as mining and cooling water.	No—concern is the discharge of the water to another location
21.	Navigation (NAV)	Uses of water for shipping, travel, or other transportation by private, military, or commercial vessels.	No—PFAS not expected to impact navigation

Refining the list of beneficial uses reduces the number of evaluations to the following groupings:

1. Aquatic toxicity to both water column and benthic organisms. This beneficial use combines those listed as WARM, COLD, EST, WILD, BIOL, RARE, and SHELL in Table 16-1.
2. Protection of human health from ingestion of PFAS when surface water is used as drinking water. Listed as MUN in Table 16-1. The values for this are already covered in Section 8 and in updated tables (the Water and Soil Regulatory and Guidance Values Table Excel file), and discussed further below.
3. Protection of human health from exposure to PFAS in the consumption of aquatic organisms, including benthic organisms. In Table 16-1 this encompasses the beneficial uses listed as COMM, AQUA, and SHELL.
4. Protection of human health from contact with and ingestion of PFAS in surface water during recreational activities such as swimming and fishing. This beneficial use is listed as REC-1 in Table 16-1.
5. Use of the surface water as an agricultural supply (AGR). Use of the surface water in this manner would allow for the uptake of PFAS into plants used for human and animal consumption, stock watering of animals used for human consumption and animal consumption, as well as recharge of excess water to groundwater or other surface water bodies (return water).
6. Groundwater recharge is also included, but the issues are the same as those for MUN, AGR, and IND as listed in Table 16-1.

These beneficial use groupings were used to identify the topics to be included in the remainder of this section.

16.1.2 Existing Methods of Protecting Surface Water for Beneficial Uses

This section provides information about the existing methods that regulatory agencies or organizations with jurisdiction use for protecting surface water bodies from discharges of various pollutants. This information provides context for what may be implemented to address potential sources of PFAS in surface water.

After establishing the beneficial uses for a given body of water (lake, stream, creek, estuary, ocean) the regulatory agency or organization implements processes designed to protect those beneficial uses. Typically, this begins with establishing water quality protectiveness standards/criteria or guidance values to protect those specific beneficial uses. As an example, to protect aquatic species, values are established for protection of the health of the fish to allow them to continue to exist in the environment and breed without curtailment. If the fish species is fished for human consumption, then values are also established to allow for fishing to occur without unacceptable effects on those consuming the fish. As values are established for each of the beneficial uses assigned for the water body, the most stringent of the values can be used as the value that is protective of all the designated beneficial uses. In that instance, that value would be used for comparison to other beneficial use values instead of individual values for drinking water and fish protection. For PFAS those values are just beginning to be established.

Once the protective value for the water body has been established, regulatory mechanisms exist to protect the water body to maintain or reduce the concentrations to below the protective values. Discharges to surface water are regulated by state- or federally issued permits. Effluent limits are established in those permits for constituents that could pose a threat to water quality. Establishing appropriate chemical-specific effluent limits protects beneficial uses. The effluent limitations are set so that the concentrations in the surface water body stay below the protective values. In addition to chemical-specific effluent limitations, the permits typically establish acceptable toxicity limitations that must be met in the total effluent. Both effluent and toxicity limitations can take into account mixing with the surface water body within a permitted mixing zone (dilution).

If a water body already has concentrations that are greater than the protective value, then the regulatory agency can establish total maximum daily loads (TMDLs). The TMDLs identify maximum mass discharges for the chemicals that exceed protective values and are used to identify mass loading limits on discharges in the watershed for that water body. Additionally, TMDLs have a component for evaluation of nonpoint sources of discharge within the watershed that include the chemical of concern. If needed, regulations of these nonpoint discharges could be adopted to also limit those discharges. Often, best management practices are established as the control mechanism for nonpoint discharges. If nonpoint discharges are the primary contributor of the pollutant, alternate approaches, such as watershed restoration plans, may be established in lieu of TMDLs. These plans can include best management practices and pollutant minimization components.

During times when a protective value is exceeded and before corrective measures are taken to bring concentrations down below those values, temporary use restrictions can be issued to protect users of the water body. Examples of such restrictions include banning recreation or issuing fish advisories that recommend restricting consumption of various fish species. If the water is being used as a source of drinking water, additional water treatment could be required.

Effluent limitations, TMDLs, watershed restoration plans, and use restrictions have been effective in protecting beneficial uses and reducing risk to receptors for numerous chemicals. It is likely that these measures will also be useful in addressing PFAS.

16.1.3 Status of State and Federal Surface Water Protection Efforts Regarding PFAS

At the time of publication, there were no national surface water values for PFAS in the U.S., and only a handful of states have addressed PFAS in surface water; see the Water and Soil Regulatory and Guidance Values Table for updates. Many of the challenges or obstacles to developing surface water criteria are the same as for groundwater, including the large number of individual PFAS, many of which lack toxicity and published physical and chemical properties data. In addition, surface water is used in a greater number of ways than groundwater, representing potential direct exposure routes through dermal contact and water ingestion, and indirect exposure through consumption of fish and shellfish. On October 18, 2021, the USEPA announced its PFAS Strategic Roadmap (USEPA 2021). The Roadmap includes actions that are planned to be undertaken by USEPA. Pursuant to the roadmap, USEPA published draft recommended ambient water quality criteria for the protection of aquatic life in June 2022 for PFOA and PFOS (USEPA 2022). USEPA also issued health advisories for PFOA and PFOS in June 2022 (USEPA 2022, 2022) and surface water quality criteria for the protection of human health are expected fall 2024. In addition, USEPA is increasing the availability of data on PFAS in fish tissue that can be used to finalize the list of PFAS for establishing fish advisories.

Enforceable vs. Nonenforceable Federal and State Values

Standard – Promulgated values that are enforceable. Example: primary drinking water standard or maximum contaminant level
Criteria – Recommended nonenforceable values that can be used to establish a standard. Example: USEPA water quality criteria
Screening/Guidance Levels – Nonenforceable values that usually represent a de minimus risk and can be used to determine if further action may be necessary. Example: USEPA regional screening levels, action-levels.

At the state level, surface water criteria development has taken a range of approaches. Alaska has adopted health advisory levels for surface water used as drinking water. These levels are used as action levels and are not enforceable under the Clean Water Act. Michigan, Minnesota, and Florida developed their own statewide criteria based on water and fish consumption using state-specific inputs and addressed PFOA and PFOS. Other states are in the process of collecting data or evaluating what approach to take to develop their own criteria in the absence of federal guidelines. Wisconsin is collecting surface water and fish tissue data to support calculation of surface water values. New Hampshire and Vermont have released detailed reports outlining potential strategies and associated costs and timing for developing state criteria. The plan from Vermont describes how its Agency of Natural Resources has developed a framework to establish water quality standards and how it may apply to developing such standards for protection of human health and aquatic life from PFAS. The report concludes that technical challenges and the constraints of deriving water quality criteria (WQC) for PFAS are “logistically difficult, would take a long time, and be very expensive.” It recommends developing fish consumption advisories, tracking USEPA development of aquatic biota criteria for PFAS, incorporating USEPA criteria when they are developed, and continued collaboration with New England states on developing plans for deriving water quality standards (Vermont DEQ 2020). The number of states that have established values for protection of aquatic life is small and includes Michigan and Florida, see the Water and Soil Regulatory and Guidance Values Table for updates to state values.

Surface water criteria are generally established by the states, either by adopting values recommended by USEPA per section 304(a) of the Clean Water Act, or by calculating state-specific criteria that must be approved by USEPA. States have specific responsibilities when setting surface water criteria and submitting that information to USEPA:

- Water bodies must have an appropriate designated use or uses.
- The WQC must support those uses.

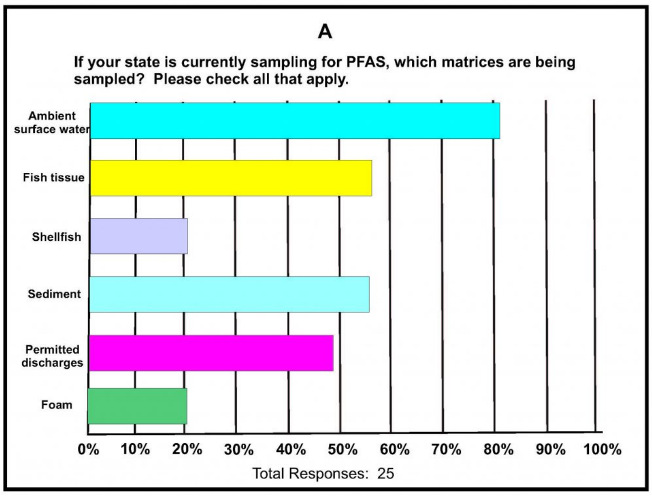
- Antidegradation policies to protect high-value waters must be adopted.
- The status of waters must be monitored.
- The standards must be revisited on a regular basis and if a revision is required, the state must obtain USEPA approval.

Most states are still in the process of assessing the extent of PFAS in their surface waters, some only at specific potential source areas.

16.1.4 Survey of States

In the spring of 2020, the ITRC PFAS team sent a survey to the states to gather information on their efforts to address PFAS in surface water. The survey included questions on what media states are monitoring for PFAS, whether PFAS have been detected in surface water, if the states have fish consumption advisories in place for any PFAS, and if the states are contemplating developing surface water quality criteria or guidelines. Other questions addressed the availability of data and information on sampling methods, PFAS-containing foam, and whether states have restrictions to minimize the discharge of PFAS to surface water.

A total of 42 states submitted responses. A summary of key responses is provided in Figures 16-1A-D. These show that of the different media being sampled, 80% of the states are sampling surface water (Figure 16-1A), and of those sampling for various PFAS in surface water, almost 60% detected one or more PFAS (Figure 16-1B). It was determined that 75% of states do not have any criteria, guidance, limits, or standards for PFAS in surface water (Figure 16-1C); however, it is noted that 16% do have some protective measure for surface water that is used as drinking water and 16% have guidance related to fish consumption advisories. Lastly, although 46% of the states were not considering development of criteria for PFAS in surface water, almost 40% felt they needed more information (Figure 16-1d); the remainder are currently developing criteria in response to proposed legislation, legislative mandates, or in response to department-level initiatives. For states that have developed surface water quality values, twice as many states reported using USEPA guidance for developing the values versus those using other procedures and methods.



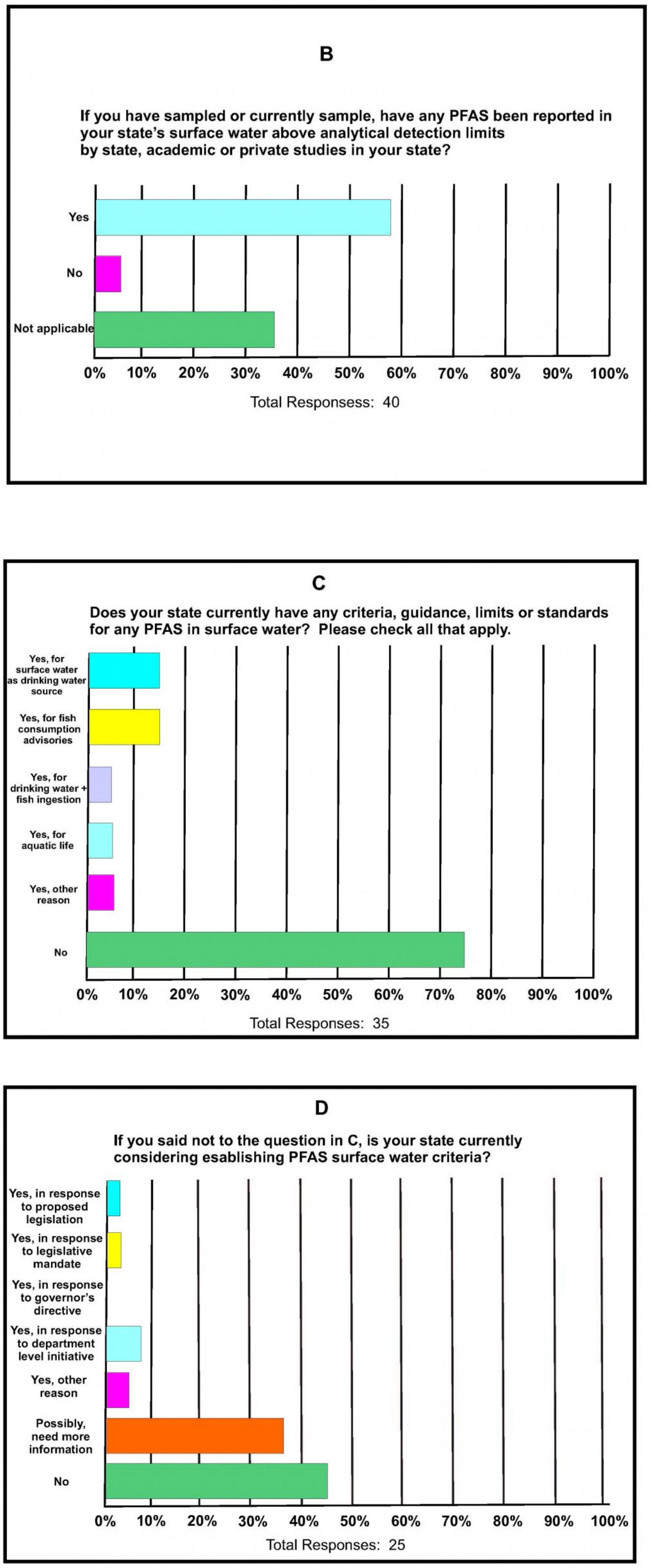


Figure 16-1A–D. Summary of Key Responses from the ITRC State Survey (2020)

Given the rapid pace in the state-of-the-science for PFAS and the desire for PFAS regulations in many states, it is likely there are updates since the time the survey was conducted. However, the PFAS team used the information from the survey to inform what areas to focus on in this surface water quality section and to document the fundamentals for states to consider when developing surface water quality protective values for PFAS. Where relevant, pertinent information from the survey is included in Sections 16.2–16.5.

For updates about states that have developed standards/guidance/limits, see the Water and Soil Regulatory and Guidance Values Table.

16.2 Protection of Human Health

This section discusses the human health aspects of PFAS in surface water. There are other sections in this document that discuss general human health–related PFAS issues in detail that supplement the information in this section. Those sections are Section 7.1, Human Health Effects and Section 9.1, Site Risk Assessment, Human Health.

Under the federal Clean Water Act, states must adopt water quality standards that consist of both designated uses and numerical and/or narrative criteria to protect these uses. As described in Section 16.1, a designated use (also called a "beneficial use" or "designated beneficial use") in some states is a use of surface waters that is considered desirable and should be protected. As noted in Table 16-1, surface waters have many different beneficial uses, some of which are relevant to human health and some that are not. Uses that are most relevant to human exposure and are considered for most chemicals include municipal and domestic supply (also referred to as drinking water use); agricultural supply (also commonly referred to as irrigation); primary contact recreation; secondary contact recreation/noncontact water recreation; commercial, subsistence, and sport (recreational) fishing (referred to in some states as fish ingestion); and aquaculture (also focused on fish ingestion).

In relation to beneficial uses, the exposure pathways for contaminants in surface water that most warrant consideration of human health for PFAS are included in Table 16-2.

Table 16-2. Exposure Pathways in Relation to Beneficial Uses

Beneficial Use	Associated Human Exposure Pathway for PFAS
Municipal and domestic supply; use as drinking water	Drinking water ingestion and dermal contact during household use; secondary uses may include irrigation for home gardening and produce consumption
Commercial, subsistence, and sport (recreational) fishing	Consumption of aquatic organisms (fish and shellfish) that may bioaccumulate PFAS from surface water
Primary contact water recreation	Incidental ingestion and dermal contact with water and/or foam during immersion activities such as swimming, waterskiing
Non-contact/secondary contact water recreation	Dermal contact with water and/or foam during nonimmersion activities such as wading, boating, fishing; exposures considered to be insignificant for PFAS
Agricultural supply	Consumption of crops, dairy products, and meat that may bioaccumulate PFAS from irrigation water; some states may also consider direct contact with irrigation water
Aquaculture	Consumption of aquatic organisms (fish and shellfish) that may bioaccumulate PFAS from aquaculture water

Regulatory agencies use relevant and appropriate use-specific exposure factors combined with chemical-specific toxicity factors (reference doses; cancer slope factors) to develop ambient water quality criteria (AWQC) that are protective of human health for these uses and exposure pathways. The exposure pathways usually considered in development of AWQC are drinking water ingestion (for waters designated for drinking water use) and consumption of aquatic organisms.

At this time, exposure pathways involving ingestion are considered to be the most significant PFAS exposure sources. Recreational uses of surface waters for secondary contact activities, such as wading and boating, which do not involve immersion but may result in dermal contact with water, are considered to be insignificant sources of PFAS exposures. See Sections 17.2.2 and 17.2.3.

Human health criteria for contaminant concentrations in surface water that are protective of fish consumption are also relevant to PFAS exposures. Additionally, some states have developed fish consumption advisories that recommend the frequency of consumption for recreationally caught fish based on levels of contaminants, including PFAS, measured in fish tissue from certain geographic regions or in specific water bodies (Section 16.2.2.6).

The salinity of the surface water body influences the beneficial uses considered and what type of criteria are appropriate (USEPA 2002, p.9). Freshwater criteria apply to waters with salinity less than one part per thousand. Saltwater criteria apply to waters with salinity greater than 10 parts per thousand. The more stringent of freshwater and saltwater criteria apply to waters with salinity between 1-10 parts per thousand. In general, saltwater criteria consider only the consumption of aquatic organisms (fish and shellfish), while freshwater criteria may consider exposure through consumption of aquatic organisms and/or drinking water. The designated uses for freshwater bodies may vary from state to state based on policy and/or actual uses as some water bodies may not support both potable use and aquatic biota consumption. Thus, criteria can be developed for the fish/shellfish consumption pathway alone or for the potable use and fish/shellfish consumption pathways combined. Surface water criteria are usually not developed for potable use alone and generally defer to guidelines such as maximum contaminant levels (MCLs) and maximum contaminant level goals (MCLGs) developed by USEPA and other agencies under drinking water programs. The combined use criterion will be more stringent than the criterion for consumption of organisms only for reasons detailed below.

16.2.1 Input Factors for Development of Surface Water Criteria and Fish Consumption Advisories

Section 16.2.2 includes information and an example equation used to develop human health criteria for relevant exposure pathways. Section 16.2.2.6 provides information and an example equation used to develop fish consumption advisory triggers.

16.2.1.1 Toxicity Values

The development of toxicity values for PFAS is an evolving and dynamic field. Changes in methodology and values, as well as the number of PFAS with toxicity values, should be expected. As a result, the information in this document is current as of March 2023 and the reader is encouraged to consult the most current information at the time of use.

The toxicity values used for both human health criteria and fish consumption advisories are oral reference doses (RfD, ng/kg/day or mg/kg/day) for noncarcinogenic effects and oral cancer slope factors (mg/kg/day)-1 for carcinogenic effects. States may base their WQC and fish consumption advisories on toxicity values recommended by USEPA or toxicity values from sources other than USEPA or develop their own toxicity values (see Section 8.3 for more detail). The toxicity values used for PFAS vary among agencies based on different choices of critical toxicological effect, uncertainty factors, exposure assumptions, and other considerations.

As of early 2023, the USEPA had either proposed or adopted toxicity factors for a limited number of PFAS but had not established surface water criteria for protection of human health. When information becomes available to develop surface water criteria for a PFAS, USEPA may follow a tiered process in selection of toxicity values, as it has done when developing criteria for other contaminants. When USEPA last updated its human health criteria (USEPA 2015), its primary source of updated toxicity values was the Integrated Risk Information System (IRIS), Other sources of toxicity values, for contaminants other than PFAS, reviewed by USEPA in its 2015 update of human health criteria include:

- USEPA Office of Pesticide Programs
- USEPA Office of Pollution Prevention and Toxics
- USEPA Office of Water
- USEPA Office of Land and Emergency Management (for example, Provisional Peer Reviewed Toxicity Values (PPRTVs))
- Agency for Toxic Substances and Disease Registry (ATSDR)
- Health Canada
- California EPA’s Office of Environmental Health Hazard Assessment

The USEPA (2015) updates used a toxicity factor from one of the non-IRIS sources listed above if no IRIS toxicity factor was available, or if the toxicity factor from another source used a newer study or a more current risk assessment approach than IRIS.

USEPA toxicity factors for a limited number of PFAS are at different stages of development and adoption for use in human health risk assessment (See Section 7.1 for information on the health effects of PFAS and Section 9.1 for information on the use of PFAS toxicity values in human health risk assessment). The USEPA's PFAS Action Plan, which was first developed in 2019 and updated in 2020 (USEPA 2020), states that USEPA will evaluate several PFAS for development of toxicity values. In addition to the reference doses that it developed for its 2016 drinking water health advisories, the USEPA (2014) generated PPRTVs for PFBS. Toxicity factors developed by USEPA's Office of Research and Development Center for Public Health and the Environment for PFBS (USEPA 2021) and by the USEPA Office of Water for GenX (USEPA 2021) serve as the basis of drinking water health advisories, but these values are currently not listed under IRIS. In late 2022, IRIS published a finalized assessment for PFBA (USEPA 2022) and is in the process of finalizing an assessment of PFHxA (USEPA 2022). Additionally, USEPA scientists are currently developing toxicity values for the following three PFAS(USEPA 2019; USEPA (2023): perfluorodecanoic acid (PFDA) (USEPA 2023), perfluorononanoic acid (PFNA), and perfluorohexane sulfonic acid (PFHxS) (USEPA 2023). USEPA Office of Water recently released draft RfDs and oral slope factors for PFOA and PFOS, as well as RfDs for PFHxS and PFNA as a part of their 2023 proposal for National Primary Drinking Water Regulations that have yet to be finalized (USEPA 2023)

16.2.1.2 Protected Populations and Target Risk Levels

The protected populations that are considered in the development of surface water criteria for human health typically include adults. In some cases, other populations, such as lactating women, women of childbearing age, children, and infants, may also be explicitly considered separately, depending on the nature of the chemical and the exposure route. As discussed in Section 16.2, the human health criteria most relevant to PFAS consider ingestion of aquatic organisms (fish and shellfish) and/or drinking water. In general, when calculating criteria for a surface water body that is used for both drinking water and fish consumption purposes, exposure from ingestion of aquatic organisms will likely be greater than exposure from drinking water for PFAS such as PFOS that bioaccumulate in aquatic life when default ingestion rates and bioconcentration factors are assumed.

In the development of human health WQC based on standard exposure assumptions, the relative doses from fish consumption and drinking water are dependent on the bioconcentration factor (BCF) or bioaccumulation factor (BAF), the target population, and their assumed intake rates. The assumed daily dose from fish consumption (22 g/day) is greater than the assumed daily dose from drinking water ingestion (2.4 L/day) for bioaccumulative PFAS such as PFOS (see Sections 16.2.1.3 and 16.2.1.4). However, exposures to bioaccumulative PFAS in drinking water are higher in infants, particularly in those that are breastfed, than in adults, and infants are considered to be a sensitive subpopulation for adverse effects of PFAS (Goeden, Greene, and Jacobus 2019). In contrast to human health criteria for surface water, drinking water guidelines for PFAS developed by USEPA (USEPA 2016, USEPA 2016) and some states are based on exposure assumptions or exposure modeling for sensitive life stages (for example, lactating women, infants (Post 2021)). Minnesota (MPCA 2020) has recently used modeling of early-life exposure in formula-fed and breastfed infants, as well as a higher fish consumption rate specific to women of childbearing age (MPCA 2020), to develop a human health surface water criterion for PFOS; they also developed a human health-based criterion for PFOS in fish tissue.

A target cancer risk level is used along with the cancer slope factor in calculation of criteria based on carcinogenic effects. The selection of the lifetime cancer risk level is a policy choice, not a scientific decision, and the target cancer risk level (for example, 1 in 100,000 or 10-5; 1 in 1,000,000 or 10-6) differs among states, which is one reason why criteria based on cancer risk can vary among different states. Criteria for noncarcinogenic effects are developed such that exposure to the contaminant will not exceed the RfD. When chemicals have the potential to exert both carcinogenic and noncarcinogenic effects (for example, PFOA), the final criterion may be based on the lower of the criteria based on cancer and noncancer effects.

16.2.1.3 Exposure Factors

The exposure factors typically considered in development of criteria for ingestion of drinking water and/or aquatic organisms include assumed body weight, drinking water and/or aquatic organism (fish/shellfish) consumption rates, and relative source contribution (RSC). These exposure factors and their use in developing criteria are described below.

As previously stated, the default adult body weight is usually used when developing human health criteria. USEPA currently recommends a default adult body weight of 80 kg for development of human health criteria (USEPA 2015). However, some states' criteria are based on the older recommended value of 70 kg. Alternative body weight assumptions for specific ages, sexes, or other subgroups can be found in the USEPA Exposure Factors Handbook (USEPA 2011), and certain states may use these values.

States typically use default ingestion rates recommended by the USEPA for the specified environmental media, for example, drinking water or fish tissue; however, some states use state-specific values, especially for fish ingestion. The adult drinking water consumption rate is usually used for human health criteria. In 2015, USEPA updated its recommended default adult drinking water consumption rate for human health criteria from 2 L/day to 2.4 L/day (USEPA 2015). It is noted that the relevant body weight-normalized exposure parameter (L/kg/day) is 0.03 L/kg/day with the updated body weight and ingestion volume, which represents a very small change from 0.029 L/kg/day based on the older values. Similarly, USEPA also updated the default rate of 22 g/day for fish consumption from the previous value of 17.5 g/day (USEPA 2015). Some states consider state- or region-specific rates that have been developed based on consumption data from their region, including higher consumption rates by tribes and/or for subsistence fishing in some cases (USEPA 2014).

Under current USEPA (2000) guidance, an RSC is used when a human health criterion is based on an RfD (noncancer effects), and USEPA used an RSC (USEPA 2015) in its updates of noncarcinogenic criteria. The RSC accounts for potential non-drinking water exposures to chemicals and is used in the development of health-based guidance and standards developed by the USEPA and related state programs. Conceptually, the RSC is the percent of total exposure assumed to come from exposure arising from surface water (ingestion of water and aquatic organisms, or ingestion of organisms only) at the criterion concentration (for example, an assumed RSC of 20% for a drinking water criterion means that the target population is assumed to be exposed to 80% of the RfD from non-drinking water sources). It is intended to ensure that total exposure from all sources (surface water and non-surface water–related) does not exceed the RfD. USEPA guidance specifies an RSC of 20–80 percent, with a default of 20 percent (the most stringent possible value) when data to derive a chemical-specific value are not available (USEPA 2015). Some states and USEPA use the 20 percent default value in their PFAS drinking water guidelines, while other states (for example, MN, NH, NY) use higher RSC values based on estimates of non-drinking water exposures from human biomonitoring data or in consideration of certain life stages.

16.2.1.4 Bioaccumulation, Bioconcentration, and Biomagnification Factors

Water to fish transfer factors are useful in the development of water quality criteria and to inform risk-based evaluations. Three types of factors can be used by risk assessors to relate environmental concentrations of a chemical (for example, in water, sediment, soil, or prey) to concentrations within certain organisms. These factors include bioaccumulation factors (BAF), bioconcentration factors (BCFs), biomagnification factors (BMFs) and associated trophic magnification factors, each of which are defined in the text box below, and detailed in Section 5.5. These factors are frequently used for risk assessment of biota such as fish and shellfish consumption by human fish consumers, as well as wildlife. The USEPA has outlined methods for developing BAFs, which are recommended for risk assessment of most chemicals, whereas BCFs and BMFs typically provide useful information about the fate, transport, and ecological risks of chemicals (USEPA 2003).

Certain PFAS are highly bioaccumulative in aquatic organisms such as fish, and this is especially true for long-chain PFAS such as PFOS. For the risk assessment of bioaccumulative and bioconcentrating chemicals such as PFAS, BAFs or BCFs should represent the tissues that are consumed by humans (for example, fillets or muscle tissue) and should also represent the trophic level of the fish species of interest (for example, secondary consumer or top-level predatory fish). Both BAFs and BCFs are specific to the chemical and organism in which it is detected. For BCFs, BAFs, or BMFs, larger values indicate greater accumulation in organisms, which in turn result in lower surface water criteria. At this time BCFs, BAFs, and BMFs for PFAS are primarily based on measured data. Examples of these values for PFAS in aquatic organisms are available in Table 5-1 (as a separate Excel file) and discussed in Section 5.5.

When the standard USEPA equation shown in the text box in Section 16.2.2 is used with standard exposure

Transfer Factors

Bioconcentration factors (BCF, L/kg) represent the direct uptake of PFAS by an organism from the water column (through the gills) and are measured as the ratio of the concentration in an organism to the concentration in water. Typically derived from laboratory studies.

Bioaccumulation factors (BAF, L/kg) represent the amount of PFAS taken up from bioconcentration plus the contribution of PFAS in the diet of that organism. Typically estimated from field studies.

Biomagnification factors (BMF; typically unitless) describe the increase in tissue concentration as one moves up the food chain based on a predator/prey relationship (always measured in the field); often defined as the concentration of chemical in an organism divided by the concentration of chemical in its food.

Trophic magnification factors (TMF; typically unitless) assumptions (drinking water ingestion – 2.4 L/day; fish consumption – 22 g/day) to develop human health criteria, the assumed contribution to total exposure from fish consumption is greater than from drinking water when the BCF or BAF is >110. As the numerical value of the BCF or BAF increases, the proportion of assumed exposure from fish consumption continues to increase. Given the mathematical impact of BAFs, BCFs, and BMFs on resulting WQC, there are several considerations for data use and applicability. One example of these considerations is the applicability of values estimated from studies on nonnative species or from water bodies with different water chemistry from the sites intended for protection. The use of central tendency versus upper percentile values may result in less stringent criteria but may be less appropriate in cases where BAFs for a given compound vary by orders of magnitude. The USEPA encourages the use of site-specific modification to BAF, BCF, and BMF selection where such decisions are appropriate and scientifically defensible (USEPA 2000).

express the change in contaminant level per trophic level, and therefore describe the biomagnification between different trophic levels of the food web.

16.2.2 Human Health Criteria Development for Beneficial Uses of Surface Water

As shown below, USEPA's standard equation for development of surface water criteria incorporates terms related to receptor characteristics, exposure, and toxicity values, as described in earlier sections.

It is noted that the USEPA (2015) updated human health ambient water quality criteria describe a similar but more complex equation incorporating trophic level–specific fish consumption rates and BAFs (or BCFs) when available. However, this approach does not appear to be applicable to PFAS since current evidence indicates that BAFs for PFAS are not clearly associated with trophic level, and trophic level–specific BAFs have not been developed for PFAS.

This section outlines issues that are relevant to development of surface water criteria for specific beneficial uses. These criteria are based on the protection of human health from exposure via intentional ingestion of contaminated media, including:

- drinking water use, 16.2.2.1
- subsistence, commercial, and sport fishing, 16.2.2.2
- drinking water combined with subsistence, commercial, and sport fishing, 16.2.2.3
- contact recreation (incidental ingestion of and skin contact with surface water, sediment, and PFAS-containing foam), 16.2.2.4
- use for agriculture, 16.2.2.5
- fish consumption advisories, 16.2.2.6.

Standard USEPA Equation for Combined Drinking Water + Fish/Shellfish Consumption

$$SWC = \frac{RfD \times BW \times RSC}{DI + ((BCF \text{ or } BAF) \times FIR)}$$

SWC = surface water criterion (mg/L)

RfD = reference dose (mg/kg/day)

BW = body weight (kg)

RSC = relative source contribution (unitless)

BCF = bioconcentration factor (L/kg)

BAF = bioaccumulation factor (L/kg)

FIR = fish ingestion rate (kg/day)

DI = drinking water ingestion rate (L/day)

USEPA (2000)

Using USEPA methodology, the surface water criteria described in Sections 16.2.2.1, 16.2.2.2, and 16.2.2.3 can be derived using a variant of the equation in the text box to the right. As described in Sections 16.2.2.1 and 16.2.2.2, terms accounting for exposure from drinking water or fish consumption can be removed as appropriate for the designated use of the water body.

The Environmental Council of the States (ECOS) published their updated white paper, Processes and Considerations for Setting State PFAS Standards in March 2023 (ECOS 2023).

16.2.2.1 Waters Designated for Domestic/Municipal Supply (Drinking Water Use)

As noted earlier, surface waters that are designated only for drinking water use may use drinking water guidelines already developed by USEPA or state agencies as WQC. Current state and federal drinking water guidelines for PFAS are found in Water and Soil Regulatory and Guidance Values Table. How certain states apply this may depend on certain regulatory considerations and authorities (ECOS 2023). Some states derive this type of surface water criterion using the equation above but omit the denominator terms for bioaccumulation/bioconcentration factors and fish ingestion rates. This equation determines a drinking water value based on human health risk assessment but does not include consideration of analytical or treatment removal factors. Additional discussion of drinking water guidelines may be found in Section 8.3.

Numerically, surface water quality criteria for the protection of drinking water may be the same as or differ from drinking water standards such as MCLs, which apply to public water systems, or ambient groundwater quality standards. Drinking water standards such as MCLs are often higher than the strictly health-based goals derived by the previously described equation because they consider analytical and treatment limitations, which consider higher values. In contrast, surface water criteria do not consider these factors. However, almost all the current state and federal drinking water guidelines for PFAS are set at health-based goals because analytical and/or treatment removal considerations are not included as limiting factors in the development of the guidelines. Some states may have the authority to adopt existing drinking water values, such as MCLs, as surface water quality criteria for the protection of drinking water sources. This varies due to states' regulatory authorities and definitions of surface waters considered acceptable for potable use. Alternatively, some states may derive criteria that differ from drinking water guidelines due to consideration of drinking water use combined with other designated uses such fish/shellfish consumption.

16.2.2.2 Waters Designated for Subsistence, Commercial, and Sport (Recreational) Fishing (Consumption of Aquatic Organisms [Fish and Shellfish] Only)

Surface water criteria for fish and shellfish consumption rely on assumptions about consumption rates as well as the relationship between chemical concentrations in water and the resulting tissue concentrations in consumed aquatic organisms.

Default fish consumption rates recommended by USEPA and choices made by states to reflect regional consumption patterns were discussed in Section 16.2.1.3. The quantifiable relationship between chemical concentrations in water and the concentrations in tissue is represented by transfer factors such as BCFs, BAFs, or BMFs, which are defined in Section 5.5 and included in the text box in Section 16.2.1.4.

The equation used to derive this type of criterion, using USEPA methods, would be the equation in the box above but omitting the drinking water ingestion rate. This equation relies on toxicity values (Section 16.2.1.1) and exposure factors (Section 16.2.1.3), as well as BAFs or BCFs for the specified chemical. More stringent toxicity values, higher exposure factors (for example, fish consumption rates), or larger BAFs or BCFs result in lower surface water criteria. For example, criteria based on the higher fish intake rates for subsistence fish consumers would be more stringent than criteria based on the average intake rates for U.S. consumers or sport fishers. Depending on state level or regional policies, such criteria may be developed separately for sport (recreational) and subsistence fishing practices. Aquaculture operations may be required to meet similar criteria for rearing, harvesting, or selling fish depending on the regulatory authority of certain states. This type of surface water criteria is typically developed in consideration of fish, especially predatory fish, as these are more commonly caught and consumed by the public than are shellfish. However, similar criteria can be developed for shellfish (for example, bivalves and crustaceans) using similar risk assessment methods.

16.2.2.3 Waters Designated for Combined Use as Drinking Water and for Subsistence, Commercial, and Sport (Recreational) Fishing

Freshwaters may support and/or be designated for both drinking water and fish consumption beneficial uses. This requires consideration of factors discussed in Sections 16.2.2.1 and 16.2.2.2. The full equation in the box above provides the USEPA method for deriving this type of criteria. Default input values would be similar to those listed for each use separately. Surface water criteria established for both drinking water and fish consumption will be more stringent than criteria for either use alone.

16.2.2.4 Waters Designated for Contact Recreation

WQC for recreational contact, such as swimming and wading, consider exposure primarily due to incidental ingestion and dermal contact with surface water, sediments, and potentially PFAS-containing foams. There is no standardized equation for development of criteria protective of exposure to recreational water, but certain equations in the USEPA's Risk Assessment Guidance for Superfund (RAGS) provide a framework for developing screening levels for recreational contact (USEPA 2004). Specifically, equations for estimating chemical intake by incidental ingestion of water and dermal absorption from water during swimming or wading are available in Chapter 3 of the RAGS Part E, Supplemental Guidance for Dermal Risk Assessment (USEPA 2004). There are several gaps in the current literature that limit the application of these equations, including scant information on skin permeability of several PFAS and how distribution in the water column influences dermal contact and potential for exposure to aerosols. Knowledge regarding volatilization and inhalation exposure is still evolving at this time.. Currently available information on partitioning of PFAS to air and the air/water interface is reviewed in Sections 5.2.4 and 5.2.4.1.

Dissolved-Phase PFAS

At this time, primary or secondary contact recreation with surface water is not expected to be a significant pathway for human exposures to PFCAs and PFSAs (for example, PFOS) as compared to drinking water or to consumption of aquatic organisms. Current evidence suggests that PFAS are poorly absorbed through the skin (discussed in Section 17.3.1.2). Studies performed by some state agencies estimated the risks associated with observed PFAS concentrations in water via recreational exposures such as swimming, and concluded that the risks were low (MDHHS 2019, MDH 2019, Vermont DEQ 2020, MPCA 2020). Recreational screening levels are likely to be orders of magnitude higher than concentrations that are protective of consumption fish/shellfish, drinking water use, or some estimates of toxicity toward aquatic wildlife. However, there is uncertainty regarding dermal absorption capabilities (for example, skin permeability coefficients) of most PFAS, both short- and long-chain, that would have a significant impact on derived guidance values. One additional area of concern may come with inhalation in an environment where water-to-air transfer may occur from aerosol-borne PFAS in sea sprays or dam mist near known source areas (Johansson et al. 2019). Knowledge in these areas and knowledge regarding the volatilization and inhalation potential of PFAS is very preliminary, still evolving, and subject to change (see Section 5.3).

PFAS in Foams

In contrast to dissolved-phase PFAS, PFAS-containing foam may occur at and above the air-water interface on surface waters (see Section 16.5 for details). However, as noted in Section 16.5, the presence of foam does not necessarily indicate the presence of PFAS. That said, observations concerning PFAS-containing foams present in surface waters have been reported in several states and present concerns for exposure from prolonged skin contact or incidental ingestion by small children. Unlike PFAS dissolved in water, foams may remain on the skin for a longer period, which may elicit public concerns. There are currently no WQC for the formation of foams, but some states may consider developing contact standards for exposure to foams. As noted above, a critical parameter in developing risk-based screening levels for recreational contact is the skin permeability coefficient, which is a measure of dermal absorption. There is currently high uncertainty and limited information available regarding skin permeability for PFAS (see Section 17.3.1.2), and this lack of data poses major challenges to risk assessment for human dermal contact with PFAS. It is anticipated that exposure to PFAS-containing foam on surface waters poses a significantly lower risk to human receptors than direct ingestion from food and water, but if combined with drinking water or occupational exposure, could pose an added toxicological burden.

Using a similar approach to that described above, along with USEPA guidance (USEPA 2000, 2011, 1989), some states may decide to develop surface water criteria for PFAS-related foams. However, these surface water criteria would likely be far higher than any criteria needed to protect surface water for other uses by humans and wildlife and would be applicable to a limited number of sites. Some states, such as Minnesota, have published qualitative guidelines (MPCA 2020). In the future, some states may develop human health-based criteria for PFAS-containing foams in surface waters that would be protective of recreational exposures such as swimming and wading. It is also challenging to sample foam in surface waters, as described in Section 16.5.

16.2.2.5 Waters Designated for Agricultural Supply

One of the beneficial uses of fresh water is agricultural supply, for irrigation of crops for direct human consumption and silage for dairy or beef livestock that may ultimately lead to indirect human consumption (milk or beef ingestion). Since PFAS are known to bioaccumulate and have been detected in edible crops, produce, dairy, and meats (Section 5.6) (ATSDR 2018;

USFDA 2019), there are potential concerns regarding acceptable levels of PFAS in surface water that will be protective of human health if used for irrigation of crops and silage.

The rapidly expanding literature about PFAS uptake into crops is useful in identifying a few general trends and is discussed in depth in Sections 5.2.3 and 5.6. The potential for PFAS bioaccumulation in plants ranges from low (0.1) to approximately 10 times the soil concentration in many studies, although plants with high water content (for example, lettuce) could exhibit considerably higher bioaccumulation of certain PFAS (see Table 5-2, provided as a separate Excel file and discussed in Section 5.6.2). Chain length is a significant factor in availability for uptake into plants. While both longer chain and shorter chain PFCAs and PFSAs may be taken up by plant roots, there is generally greater translocation and distribution of shorter chain PFAS into the remainder of the plant, including the aboveground tissues (Section 5.6.2). In general, there is greater accumulation in vegetative tissues (for example, leaves and stems) than in storage tissues such as fruits and seeds (Section 5.6.2).

There is currently no USEPA guidance for development of surface water criteria for irrigation and livestock watering. However, approaches have been developed by some states, and other countries such as Canada (ECCC 2017), that consider human dermal and inhalation exposure to irrigation water and consumption of irrigated produce (for example, University of Florida (2018)). These references may be consulted for additional information on irrigation and livestock protection.

16.2.2.6 Fish Consumption Advisories Based on Consumption Frequency

Fish consumption advisories are health-protective recommendations developed by states for frequency of consumption of recreationally caught fish meals. These advisories may be applicable statewide, in certain regions of a state, or to specific water bodies or reaches/segments of water bodies. Fish consumption advisories are not surface water criteria and are not regulatory in nature. The advisories may be issued for the general public, and they may be more stringent for specific groups of people at higher risk, such as women of childbearing age, pregnant or nursing women, or children. At the time of publication of this document, several states (for example, AL, CT MI, MN, NJ, WI) have issued fish consumption advisories for PFAS, particularly PFOS.

Advisories are developed by comparing fish tissue concentrations in wet weight (“triggers”) that do not result in unacceptable risks for consumption of meals at different frequencies (for example, unlimited [daily]; once per week, once per month, once per year) with concentrations of the contaminant measured in fish tissue. The advisories may be species- and water body–specific, based on data for PFAS tissue concentrations from the species in the water body, or they may apply regionally and/or to multiple species. Typically, limits are developed for muscle fillets of commonly caught and consumed fish, often accompanied by a recommendation to avoid consumption of skin, fat, and other nonmuscle parts of the fish. If there are populations whose consumption patterns exceed the assumptions of the advisory (for example, consumption of whole fish), there may be a potential for insufficient protection.

Assumptions and parameters used in the calculation of fish tissue trigger levels include:

1. the reference dose for each PFAS
2. a consumer’s body weight (BW)
3. the size of the fish meal

The generalized equation for development of fish tissue trigger concentrations based on noncancer effects used for fish consumption advisories are shown in the text box; a different equation (not shown) would be used for advisories based on cancer risk.

Standard USEPA Derivation of Fish/Shellfish Tissue Trigger Concentrations Used in Development of Consumption Advisories

$$\mathrm{DTC} = \frac{\mathrm{RfD} \times \mathrm{BW}}{\mathrm{MS}}$$

Where:

DTC = trigger concentration for daily consumption (µg/g)

BW = assumed human body weight (kg)

RfD = chronic oral reference dose (µg/kg/day)

MS = meal size (g/day)

Trigger concentrations for daily consumption are based on calculation of the concentration of a contaminant in fish tissue that results in exposure equal to the RfD from a fish meal. Trigger concentrations for less frequent meal consumption are calculated by multiplying trigger concentration for daily consumption by appropriate factor (for example, daily – 7; monthly – 30).

USEPA (2000)

16.3 Protection of Biota

16.3.1 Overview and Purpose

This section presents the technical methods and information needed to develop or review surface water criteria for PFAS that would be protective of aquatic life and their uses. There are other sections in this document where general ecological issues associated with PFAS are discussed in detail, and that information supplements the information contained in this section. That additional information can be found in Section 7.2, Ecological Toxicology, and Section 9.2, Ecological Risk Assessment. Section 16.3.2 provides information regarding ecotoxicological data for assessing water quality criteria for PFAS that were available during development of previous versions of this document and still provides a starting point for evaluation of available values. The section is not intended to present an exhaustive compilation of the currently available data as this is an active field of research in which new information is regularly provided. It is recommended that the reader search for updated ecotoxicological data prior to development of water quality criteria for the protection of wildlife.

The types of aquatic life to be protected are usually defined by the various beneficial uses related to surface water that are described in Section 16.1.1. USEPA guidance (USEPA 1985) for derivation of such criteria are primarily intended to protect all but the most sensitive aquatic organisms from exposure to chemicals in surface water or sediment porewater. Considerations also exist to derive criteria for protection of aquatic-dependent avian and mammalian wildlife via calculation of a “final residue value” that can factor into final selection of the chronic criterion (USEPA 1985), or a more explicit “wildlife criterion” using methods presented for the Great Lakes Initiative (GLI; (USEPA 1995)).

Aquatic life criteria share the levels of protection afforded by the Clean Water Act and USEPA guidelines (USEPA 1985) in that criteria are derived using toxicity tests with aquatic organisms in which survival, growth, and reproduction are measured. These data are compiled to derive criteria intended to protect against unacceptable adverse effects to most animal taxa in the aquatic community, which is most commonly calculated to represent protection of approximately the 95th percentile of tested aquatic genera. As a result, acute and chronic criteria concentrations are generally said to represent protection of all but 5% of the most sensitive aquatic species. Criteria can also be lowered to protect particularly important species such as recreationally or economically important species or listed threatened or endangered species.

The following sections summarize the general USEPA methods available for derivation of aquatic life criteria for PFAS, with a focus on how to select the most appropriate toxicity test endpoints related to USEPA guidance (USEPA 1985). Available ecotoxicity data are then summarized for all freshwater and marine aquatic species relevant for derivation of aquatic life criteria, including invertebrates, vertebrates, and algae/vascular plants. This section closes with a summary of information necessary to develop criteria to protect aquatic-dependent wildlife such as birds or mammals, including permissible tissue PFAS concentrations, bioaccumulation and bioconcentration factors, and other food chain effects.

16.3.1.1 Derivation of Aquatic Life Protection Criteria—Methods Summary

The general approach for derivation of aquatic life criteria, according to USEPA guidance (USEPA 1985), is briefly summarized below, along with the definition of key terms. The first step is to compile acute and chronic toxicity data that meet the USEPA (1985) guidelines for the relevance and reliability of each study. This evaluation for scientific relevance and reliability largely focuses on test duration, survival in the control treatment, and methods, with distinctions made between acute (short-term) or chronic (long-term) studies. For example, acute toxicity studies must have an exposure duration of 96 hours (although 48 hours is acceptable for more short-lived species, such as cladocerans and midges), organisms must not be fed during the study, and the endpoint must be mortality, immobilization, or a combination of the two. Chronic toxicity studies must be conducted using exposure durations that encompass the full life cycle or, for fish, early life stage and partial life cycle studies. The acceptable endpoints for chronic tests include survival, growth, and reproduction (see Section 16.3.1.4). The duration of chronic studies may be many days, weeks, or months.

To develop criteria that are protective of the diverse array of aquatic biota, an extensive database representing multiple test species, genera, and taxa is required. A minimum database of acceptable studies representing at least eight specific taxonomic families of aquatic organisms is also required. This is done to ensure that criteria are derived based on data that represent the widest possible range of likely sensitivities encountered in the environment. These minimum database requirements differ for freshwater versus saltwater species as presented in Table 16-3.

Table 16-3. Minimum database requirements for derivation of aquatic life criteria (USEPA 1985)

Freshwater	**Saltwater**
A bony fish in the family Salmonidae	Two families in the phylum Chordata
A second family of bony fish (preferably a commercially or recreationally important warm water fish)	A family in a phylum other than Arthropoda or Chordata
A third family in the phylum Chordata	Either the Mysidae or Penaeidae family
A planktonic crustacean	Three other families not in the phylum Chordata (may include Mysidae or Penaeidae, whichever was not used above)
A benthic crustacean	Any other family
An insect	
A family in a phylum other than Arthropoda or Chordata	
A family in any order of insect or any phylum not already represented	

For each species with acceptable acute toxicity data, the species mean acute value (SMAV) is calculated as the geometric mean of available 48- to 96-hr median lethal concentrations (LC50s) or median effect concentrations (EC50s) for each species. The genus mean acute value (GMAV) is then calculated as the geometric mean of available SMAVs for each genus. The lowest 5th percentile of the distribution of available GMAVs is identified as the final acute value (FAV), which is divided by two to determine the criterion maximum concentration, which is more commonly termed the "acute criterion." The criterion continuous concentration, or "chronic criterion" can either be calculated using the same 5th percentile calculation as the FAV if all eight minimum database requirements are met, or if they are not met by dividing the FAV by the ratio of acute to chronic effects, termed the acute to chronic ratio (ACR). The ACR is determined from those species with both acute and chronic data available usually as a geometric mean of the available species ACRs. ACR values are one of the factors used to derive chronic surface water criteria for chemicals (USEPA 2008). They may also be used in the development of aquatic life screening values when acute toxicity data may be available but not enough chronic toxicity data are available for a chemical. Generally accepted ACR values have not yet been developed for PFAS and would need to take into account the diversity of chemical structures and behavior of PFAS. See the discussion in Section 16.3.2 regarding the availability of acute and chronic data for select PFAS.

16.3.1.2 Problem Formulation

Recently, USEPA has been developing ambient water quality criteria documents following an ecological risk assessment framework (USEPA 1992) to provide a logical approach to criteria derivation based on the chemical's characteristics, fate and transport, and mode of toxic action. This information for PFAS is summarized below to assist with the development of a conceptual model and identification of endpoints needed for states to derive aquatic life criteria.

16.3.1.3 Conceptual Model

A conceptual model consists of a written and/or graphical representation of the linkages between the exposure characteristics of the chemical and the ecological endpoints of relevance to criteria derivation. PFAS will be transported to surface waters from direct soil runoff, groundwater discharge, atmospheric deposition, or point source discharges (see Figure 17-1). Once transported into surface waters, PFAS exposures to aquatic organisms will occur via two main pathways: direct from water (bioconcentration) and via the organism's diet as well as water (bioaccumulation). These pathways are also described and quantified in Section 5.5.

Biomagnification is also an important factor for some PFAS (for example, those with carbon chain lengths of eight or more) (Section 5.5). Section 16.3.3 describes procedures to evaluate uptake of PFAS in aquatic-dependent wildlife.

This simple conceptual model suggests that aquatic life criteria for PFAS will need to consist of two different kinds of toxicological information:

- Toxicity data generated from water-only exposures

- Toxicity data with effects measured on the basis of receptor tissue concentration and diet, from which bioaccumulation and bioconcentration factors are estimated to back-calculate to a protective PFAS concentration in water (see Section 16.3.3.3).

Toxicity data measured on the basis of receptor tissue concentration can also be used to derive purely tissue-based aquatic life protection criteria for PFAS. Tissue-based aquatic life criteria would be subject to less uncertainty because the effects levels directly relate toxic dose and exposure pathways, and because BAFs or BCFs would not be needed to back-calculate to a water concentration. This approach has recently been used for methylmercury (USEPA 2010) and selenium (USEPA 2016) in fish in which tissue-based criteria concentrations take precedence over water column-based concentrations.

16.3.1.4 Assessment Endpoints

Assessment endpoints represent the expression of environmental values to be protected by the management framework (USEPA 1992). In the case of ambient water quality criteria, the values to be protected are aquatic life and their uses. As discussed in Section 16.3.1, the levels and types of protection are those afforded by the Clean Water Act and USEPA guidelines (USEPA 1985). These guidelines specify protection of all but 5% of the most sensitive aquatic organisms with respect to survival, growth, and reproduction.

16.3.1.5 Measurement Endpoints

Measurement endpoints represent the direct empirical measurements of chemical exposure and biological effects that are used to ultimately represent the assessment endpoint (USEPA 1992). For PFAS, the relevant measurement endpoints are as follows:

- Measures of exposure: Given the conceptual model noted above, PFAS measurements would need to include both direct aqueous concentrations and aqueous concentrations estimated using appropriate bioaccumulation or bioconcentration factors (see Section 16.3.3 and Section 9.2.2). Sufficient single chemical toxicity data for aquatic life criteria mainly exist for only PFOA and PFOS, although Tier II methods have been used by Giesy et al. (2010) for PFBS and by Divine et al. (2020) for acute and chronic values for 21 PFAS. Mixture studies for commonly detected PFAS are limited with no consensus on additivity, synergism, or antagonism. Thus, it is difficult to determine at this time whether measures of exposure could be considered additive for either PFOA + PFOS, or even for other PFAS.
- Measures of effect: According to USEPA guidance (USEPA 1985), measures of effect (either acute or chronic) are limited to those representing survival, growth, and reproduction. Therefore, only PFAS toxicity endpoints that either directly measure, or can directly represent, these endpoints should be used for derivation of aquatic life criteria. According to toxicity data summarized in Section 16.3.2 below (and in Section 7.2), available PFAS toxicity endpoints include several sublethal endpoints that could potentially be used to represent growth or reproduction. These include endpoints such as development, percent emergence, time to metamorphosis, and development of malformations. Therefore, states will need to determine whether or not these sublethal effects can be considered reliable quantitative measures of chronic effects of relevance to development of criteria. USEPA developed some logical considerations for this determination relative to endocrine-disrupting chemicals. These considerations may be applicable to PFAS (USEPA 2008).

16.3.2 Availability of Ecotoxicological Data

Toxicity data for establishing surface water quality criteria are available in peer-reviewed sources, mainly the primary literature. As noted in Section 7.2, most aquatic toxicity data are for PFOS, PFOA, and several other PFAS, including PFNA, PFBA, and PFBS. USEPA has curated peer-reviewed sources of ecotoxicity data for PFAS into the USEPA Ecotoxicology (ECOTOX) Knowledgebase (USEPA 2023). In addition, as stated in Section 16.1, USEPA has published draft national recommended aquatic life criteria for PFOA and PFOS in freshwater for public comment (USEPA 2022, 2022) and a fact sheet for the criteria (USEPA 2022). Furthermore, USEPA has published their responses to external peer reviews of the draft criteria (USEPA 2022, 2022).

This section provides a high-level overview of the available ecotoxicity data retrieved at the time and does not represent an exhaustive literature review for the classes of organisms specifically required for developing aquatic life surface water quality criteria. As noted in Section 7.2, the ecological toxicology of PFAS is an active area of research and users are encouraged to query the literature for updated values. Furthermore, states that undertake criteria development should review the studies discussed here and others that are subsequently published to determine if they meet regulatory requirements prior to using them for WQC development.

When developing surface water quality criteria protective of aquatic receptors, several criteria should be met when selecting appropriate studies, such as inclusion and adequate control animal responses and availability of details on experimental design. Test animals should be native and have reproducing wild populations. Also, note that many published endpoints are based on nominal rather than measured PFAS exposures; where measured concentrations are used, they can range from very low to very high percentages of the nominal values (<10–240%). Thus, it is recommended to use measured concentrations for establishing criteria.

The following sections highlight available data, or lack thereof, for the various taxonomic families required for WQC development (refer to Table 16-3 and Section 16.3.1.1).

16.3.2.1 Bony Fish

Aquatic criteria development requires toxicity data for a salmonid species and one other species of bony fish. Fish toxicity studies are mainly focused on PFOS, for which data for multiple bony fish species (for example, rainbow trout (*Oncorhynchus mykiss*), sheepshead minnow (*Cyprinodon variegatus*), fathead minnow (*Pimephales promelas*), and zebrafish (*Danio rerio*) are available. As discussed in Section 5.5, PFOS preferentially accumulates in fish tissue relative to other PFAS. Overall, the data for other PFAS are generally limited to a single species or are lacking entirely (see Section 7.2).

16.3.2.2 Salmonids

Acute salmonid studies on the rainbow trout (*O. mykiss*) have been conducted under both fresh- and saltwater conditions for PFOS. EC50 range from 17 mg/L to 22 mg/L (Robertson 1986; Palmer, Van Hoven, and Krueger 2002); a no observed effect concentration (NOEC) was reported at 6 mg/L (Palmer, Van Hoven, and Krueger 2002). No chronic studies were identified for this or other salmonid species.

16.3.2.3 Other Fish Species

Several acute and chronic studies are available for non-salmonid species (see Section 7.2) and for PFAS other than PFOS. Data from these studies indicate acute toxicity of PFOS on the same order of magnitude as that observed for the rainbow trout, with some species perhaps even more sensitive; LC50s for zebrafish (*D. rerio*; a freshwater native to Asia*)* and fathead minnow (*P. promelas*, a freshwater native to North America*)* were approximately 10 mg/L, with EC50 and NOECs ranging between 1.5 and 3 mg/L (Drottar and Krueger 2000; Ulhaq et al. 2013). Data from an acute test on the North American saltwater species sheepshead minnow (*C. variegatus*) for PFOS suggest this species is less sensitive than its freshwater counterparts, with EC50 greater than 15 mg/L (Palmer, Van Hoven, and Krueger 2002).

Chronic studies of PFOS toxicity are more limited; only two studies of *P. promelas* were identified and indicated a NOEC of approximately 0.3 mg/L and EC50 of 7 mg/L (Drottar and Krueger 2000; Oakes et al. 2005) for early life stage development.

Acute and/or chronic zebrafish toxicity studies are also available for PFOA, PFBS, PFNA, PFBA, and PFDA. Acute toxicity is highly variable, but in general, these compounds appear to be less toxic than PFOS, with LC/EC50 reported up to 3,000 mg/L; the exception to this generality is PFDA, where an EC50 of 5 mg/L was reported (Ulhaq et al. 2013). Chronic toxicity data in this species for these compounds are more limited, but the few available studies suggest chronic toxicity may occur at substantially lower concentrations; for example, Zhang et al. (2012) reported a LOEC of 0.01 mg/L for growth/weight was for PFNA.

16.3.2.4 Other Aquatic Chordates—Amphibians

Amphibians represent an alternative class of aquatic/semi-aquatic chordates for which PFAS toxicity studies have been conducted. There are currently limited PFAS toxicity data available for amphibians, but this class of organisms is becoming more widely studied. Nearly all the available amphibian studies entail acute studies in aquatic life stages (with mortality as the endpoint) on PFOS exposures to several species, including Xenopus laevis (African clawed frog), Rana pipiens (northern leopard frog), Rana nigromaculata (black-spotted frog), Pseudocris crucifer (spring peeper), Lithobates catesbeianus (American bullfrog toad), and Bufo gargarizans (Asiatic toad). Of these, R. pipiens L. catesbeianus, and P. crucifer are native to North America. Amphibian data are discussed in Section 7.2 for PFOS and PFOA. These studies indicate mortality is observed in amphibians at water concentrations over 10 mg/L, with chronic toxicity occurring at lower levels (although within the range of acute toxicities), and that PFOA is less toxic than PFOS.

16.3.2.5 Crustaceans

Freshwater

Acute

Acute toxicity data for freshwater crustaceans are focused on various daphnids (see USEPA 2023), with some data on freshwater shrimps such as the cherry shrimp (*Neocaridina denticulate*) (Li 2009). The largest number of publications are on the water flea, *Daphnia magna*, where 24–48-hour survival data are available for PFBA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA, and PFOS. For most other freshwater species, acute toxicity data are limited to PFOA and PFOS.

Chronic

A smaller number of specific PFAS have been assessed for chronic toxicity in freshwater crustaceans. This includes PFOA, PFBS, PFOS, and GenX salt (ammonium 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)-propanoate) (Drottar and Krueger 2001). The 21-day survival and reproduction assay with daphnids is reported for both PFOS and PFOA Section 7.2). A series of studies evaluated bioavailability of certain PFAS with respect to exposure cofactors such as dissolved proteins, organic carbon composition, and other solutes (Xia et al. 2015; Xia et al. 2015; Xia et al. 2013). Although these studies do not estimate ECs or LCs for specified PFAS, they demonstrate that abiotic factors require consideration for exposure assessment and comparison across aquatic toxicity studies.

Saltwater

Acute

Two short-term studies (96 hours) provide some data on the acute toxicity of PFOS in marine crustaceans. The two tested species, both mysid shrimp, are *Siriella armata* and *Mysidopsis bahia,* for which NOECs of 0.550—1.25 mg/L (Drottar and Krueger 2000; Mhadhbi et al. 2012) were derived; however, the values for *S. armata* were based on nominal concentrations (Mhadhbi et al. 2012). Additional studies are needed to evaluate other PFAS, as well as to discern differences in acute toxicity among benthic, epibenthic, and pelagic crustacean species.

Chronic

There are very few laboratory-based chronic toxicity studies available for marine crustaceans. One study was a 35-day growth, reproduction, and survival assay for PFOS using mysid shrimps (*Mysidopsis bahia*) (Drottar and Krueger 2000); (see Section 7.2). Simpson et al. (2021) more recently conducted a comprehensive study of PFOS sediment, overlying water, and/or porewater exposure to various benthic marine/estuarine species, reporting chronic effects data for an amphipod (*Melita plumulosa*), a copepod (*Nitocra spinipes*), and a crab (*Macrophthalamus* sp.).

While there are multiple studies regarding the occurrence of PFAS in wild-caught crustaceans, there is little information on biological effects. There is one recent report on wild-caught eastern school prawn (*Metapenaeus macleayi*) that found associations between metabolomic profiles and certain PFAS, but the exposure history for the animals was unknown (Taylor et al. 2019).

16.3.2.6 Mollusks

Freshwater

Acute

For freshwater mollusks, toxicity studies of PFOA and PFOS are limited to five species: bladder snail (*Physa acuta*), fatmucket clams (*Lampsilis siliquoidea*), black sandshell mussels (*Ligumia recta*), *Unio ravoisieri,* and zebra mussels (*Dreissena polymorpha*) (Li 2009; Hazelton et al. 2012; Fernández-Sanjuan et al. 2013; Amraoui, Khalloufi, and Touaylia 2018). The fatmucket and black sandshells are native to North America, whereas the remaining three are nonnative to the U.S. or are invasive species, as in the case of zebra mussels. Following 24- to 96-hour exposures, Hazelton et al. (2012) estimated lower EC50s for PFOS than for PFOA in both fatmucket clams and black sandshell mussels, where larvae were more sensitive than juveniles toward PFOS.

Chronic

Assessments of chronic effects in freshwater mollusks are limited to a single study with water concentrations that were much higher than those detected at most remediation sites. Following a 28-day exposure to PFOS, Hazelton et al. (2012) observed impaired growth effects in larval and juvenile fatmucket clams as determined by reductions in larval viability (LOEC of 0.0045 mg/L) and impaired metamorphosis (LOEC of 0.0695 mg/L), respectively. Fernández-Sanjuan et al. (2013) evaluated the physiological responses of nonnative and invasive zebra mussels toward a mixture of PFOA and PFOS (0.001—1 mg/L, 10 days), but did not report any mortality.

Saltwater

Acute

Acute toxicity studies for marine mollusks are currently limited to PFOA, PFNA, PFOS, and PFDA. A larger body of literature exists on occurrence and tissue concentrations in mussels and oysters, but almost none of these assessed whole or suborganism level effects. Two 96-hour acute toxicity tests reported NOECs for mortality in *Unio complamatus* (20 mg/L) and eastern oyster (*Crassostrea virginica*) (18 mg/L) (Drottar and Krueger 2000).

Chronic

Chronic studies for sublethal effects of PFAS on bivalve mollusks are limited to a few marine species, including green mussels (*Perna viridis*), Mediterranean mussels (*Mytilus galloprovincialis*) and California mussels (*Mytilus californianus*). In vitro and in vivo studies of California and Mediterranean mussels offer some information relative to effects on xenobiotic transport proteins and enzymatic activities, respectively (Stevenson et al. 2006; Balbi et al. 2017; Gülsever and Parlak 2018), but do not quantify ECs, NOECs, or LOECs for whole-organism exposures. A series of studies using green mussels reported on multiple endpoints following 7-day exposures to PFOS, PFOA, PFNA, and PFDA. These studies evaluated biochemical markers of altered xenobiotic metabolism (Liu, Gin, and Chang 2014), genotoxicity (Liu et al. 2014), oxidative stress (Liu, Chang, and Gin 2014), and immunotoxicity (Liu and Gin 2018) and reported NOECs ranging from 0.010-0.100 mg/L (PFOA and PFNA) down to 0.001-0.01 mg/L (PFOS and PFDA). Simpson et al. (2021) reported chronic no-effects levels for two species of bivalve mollusks (*Tellina deltoidalis* and *Soletellina alba*) of 0.22 mg/L and ≥ 0.85 mg/L, respectively.

16.3.2.7 Aquatic Insects

Freshwater

Toxicity data for aquatic insects (for example, midges, mayflies, dragonflies) are available in the literature, although they mainly stem from acute studies of PFOS, PFOA, and PFNA in the freshwater midge species *Chironomous riparius* and *C. tentans* (see Section 7.2.2.1). Of the aquatic invertebrate species, the chironomids are currently reported as having the highest sensitivity to PFOS (MacDonald et al. 2004). Acute effects are observed to generally occur at water concentrations of approximately 60 mg/L or greater, with chronic effects induced at concentrations less than 0.002 mg/L (see Section 7.2.2.1).

Toxicity data for other orders of aquatic insects are very limited, although some studies indicate that the odonates may also be highly sensitive to PFAS exposures. Van Gossum et al. (2009) found behavior changes following long-term (4-month) exposure of PFOS to damselflies (*Enallagma cyathigerum*) with NOECs reported from 0.010 mg/L to 0.100 mg/L. Bots et al. (2010) conducted a lifetime exposure study of PFOS on *E. cyathigerum*, finding adverse effects on egg development, larval hatching, development and survival, metamorphosis, and body mass, with NOECs ranging from less than 0.010 mg/L (for metamorphosis) to over 10 mg/L (for egg hatching success).

Saltwater

No toxicity information was found on marine insects.

16.3.2.8 Algae/Vascular Plant Data

Section 7.2.4.1 provides a summary of aquatic plant toxicity data. Data on the toxic effects of PFAS on aquatic plants are limited to studies that evaluated PFOS exposures on several algal/microalgal species, on duckweed (*Lemna gibba*), and on watermilfoil (*Myriophyllum spicatum)*. Acute toxicity of PFOS in freshwater aquatic plants has been found to range from approximately 30–100 mg/L, with chronic values generally about tenfold lower.

In a chronic study on a saltwater species of diatom (*Skeletonema costatum*) Desjardins et al. (2001) reported observed effects at approximately 3 mg/L. Simpson et al. (2021) reported a chronic NOEC of > 4.2 mg/L for growth rate as an endpoint.

16.3.3 Aquatic-Dependent Wildlife

This section considers aquatic-dependent wildlife (primarily birds and mammals) in developing surface water criteria for PFAS. It is important to note that the development of such criteria is still in its infancy because (i) there are few laboratory or field studies with data on the toxicity of PFAS to wildlife, (ii) data of sufficient/appropriate quality on the concentration of PFAS in the diet of aquatic-dependent wildlife are limited, and (iii) the unique properties of PFAS make the modeling of food chain uptake complicated. The following sections briefly discuss why aquatic-dependent wildlife should be considered and present methods that can be used to derive surface water quality criteria for their protection.

16.3.3.1 Why Consider Aquatic-Dependent Wildlife?

As described in Section 16.3.1, the focus for deriving surface water quality criteria is primarily on protecting aquatic life (for example, plankton, benthic invertebrates, fish, shellfish). However, it has long been recognized that wildlife species may be more sensitive than aquatic species toward certain contaminants as a result of dietary exposure, particularly if the contaminant is bioaccumulative (USEPA 1985, 1989, 2005).

Because some PFAS are known to be bioaccumulative (see Section 5.5), it cannot be assumed that surface water quality criteria derived for the protection of aquatic life will also be protective of aquatic-dependent wildlife. Protection of aquatic-dependent wildlife is of importance at contaminated sites, particularly for wildlife with smaller home ranges that coincide with the extent of PFAS impacts (Conder et al. 2020; Divine et al. 2020). In developing risk-based screening levels (RBSLs) for different classes of receptors, Divine and coworkers found that for some PFAS, RBSLs for aquatic-dependent wildlife are lower than RBSLs for aquatic life. Lastly, due to the long-range transport for some PFAS (see Section 5.3), there could be a need for surface water quality criteria protective of aquatic-dependent wildlife in remote areas where management actions to address human exposure may not address ecological exposures.

16.3.3.2 Surface Water Quality for the Protection of Wildlife

The principal approach to developing protective surface water quality for wildlife is to use standard desktop wildlife exposure models to solve for a media concentration that results in exposure being equal to a selected toxicity threshold. In modeling exposure, such an approach either uses measured contaminant concentrations in the tissue of the prey/forage or relies on BAFs (to estimate prey/forage tissue concentrations). The same toxicity threshold can be used in either case. Another approach is to determine a critical concentration in the tissue of a prey item that is protective of the wildlife receptor. The advantage of this "body burden" approach is that it avoids the uncertainties associated with relying on BAFs; however, it entails the collection of site-specific tissue data for implementation.

These two approaches are discussed in the following sections.

16.3.3.3 Calculation of a Protective Surface Water Quality Value for Aquatic-Dependent Wildlife

In 1995, USEPA published the Great Lakes Water Quality Initiative (GLI) Technical Support Document for Wildlife Criteria (USEPA 1995). The GLI Technical Support Document provided technical information on the derivation of surface water quality criteria to protect birds and mammalian wildlife. The method is similar to that used to derive noncancer human health criteria and relies on the use of BAFs in a food chain model to back-calculate a surface water value (USEPA 2017). USEPA has used this method for chemicals such as DDT, PCBs, 2,3,7,8-TCDD, and mercury, for which aquatic life-based criteria were modified to become more stringent in order to incorporate adverse effects to wildlife (USEPA 1995). States and tribes bordering the Great Lakes, as well as other states, such as California, have since adopted this approach to derive aquatic-dependent wildlife surface water quality criteria.

The GLI Technical Support Document (USEPA 1995), Section III, provides the equations needed to calculate a protective surface water quality value for birds and mammals from exposure via food and water ingestion (see text box).

By extension, this method can be used in the development of surface water values for PFAS. The GLI approach uses five representative species (bald eagle, herring gull, belted kingfisher, mink, and river otter), because these species are likely to be subjected to the highest exposure from bioaccumulative contaminants through the aquatic food web. However, depending on the conceptual model under evaluation, it might be more appropriate to select different representative

Standard Equation for Derivation of a Protective Surface Water Quality Value for Aquatic-Dependent Wildlife

$$\text{WV (mg/L)} = \frac{\text{TD (mg/kg bw/d)} * (1/(\text{UF}_A * \text{UF}_S * \text{UF}_L)) * \text{BW (kg)}}{\text{W (L/d)} + \text{sum}\,[\text{FC}_i \text{ (kg food/d)} * \text{BAF}_i \text{ (L/kg)}]}$$

Where:

species (for example, sandpiper species given their relatively high incidental ingestion of sediment). Giesy et al. (2010) provided good examples of using the GLI approach to calculate surface water criteria for trophic level IV predatory birds for two compounds, PFOS and PFBS.

The GLI Technical Support Document includes tables with values for the exposure parameters (body weight, water and food ingestion rates, as well as prey/forage trophic level). Other sources of receptor-specific exposure parameters can be found in USEPA's Wildlife Exposures Factor Handbook USEPA (1993), Conder et al. (2020), and Divine et al. (2020). However, it is a best practice to select exposure parameters that are most representative of the populations living within the area to which the criteria will be applied. Climate, temperature, habitat, and many other factors specific to the region underlying the studies that are the basis of the exposure factors can vary significantly.

Key PFAS-specific components to this approach are the selection of, and sources for, BAFs to estimate prey or forage tissue concentrations, and the wildlife toxicity data for PFAS (no observed adverse effect levels [NOAELs] and lowest observed adverse effect levels [LOAELs]).

As noted in Section 16.2.1.4, given the influence of BAFs on calculation of a water quality value, their use and applicability need to be carefully considered. Information on a literature review and selection of BAFs is provided in Section 5, with a compilation of BAFs and their sources presented in Table 5-1 (see link in Section 5.5).

WV = wildlife value in milligrams of substance per liter (mg/L)

The bird WV is the geometric mean of the WVs calculated for the three birds and the mammalian WV is the geometric mean of the WVs calculated for the two mammalian wildlife species.

TD = test dose in milligrams of substance per kilogram per day (mg/kg-d) for the test species. This shall be either a NOAEL or a LOAEL (expressed either on a wet weight or dry weight basis for consistency with FC).

UF_A = uncertainty factor (UF) for extrapolating toxicity data across species (unitless). A species-specific UF shall be selected and applied to each representative species, consistent with the equation.

UF_S = UF for extrapolating from subchronic to chronic exposures (unitless)

UF_L = UF for LOAEL to NOAEL extrapolations (unitless)

BW = body weight in kilograms (kg) for the representative species

W = daily volume of water consumed in liters per day (L/d) by the representative species

FC_i = daily amount of food consumed from the i^{th} trophic level in kilograms per day (kg/d) by the representative species (expressed either on a wet weight or dry weight basis for consistency with TD)

BAF_i = bioaccumulation factor for the i^{th} trophic level in liters per kilogram (L/kg)

As noted, there are currently few PFAS toxicity data for wildlife in the scientific literature or standard toxicity databases. Furthermore, given the minimum toxicity database requirements for developing Tier I criteria (see USEPA (1995)), it is unlikely these requirements will be met for individual PFAS at the current time. Note that the GLI technical support document does provide guidance on developing Tier II wildlife values for contaminants with limited toxicity data (USEPA 1995). Conder et al. (2020) and Divine et al. (2020) are good sources of PFAS toxicity reference values (TRVs) for avian and mammalian wildlife that not only include tables of recommended values, but also provide guidance on reviewing toxicity studies reported in the literature and selecting the values.

16.3.3.4 Calculation of a Protective Prey/Forage Tissue-Based Value

USEPA published a science advisory board consultation document on tissue-based criteria for "bioaccumulative" chemicals as proposed revisions to aquatic life guidelines (USEPA 2005). The approach is based on the recognition that for bioaccumulative chemicals, there is a need to develop criteria that account for multiple routes of exposure such as the diet, sediment, and water.

The approach is similar to that for developing a water-based value in that it is based on a daily dietary dose of a chemical that is protective of most sensitive species and integrates it with exposure potential to estimate a chemical concentration in the dietary tissue of representative species, also referred to as a wildlife value (WV). The advantage of this approach over the water-based approach is that it eliminates the uncertainty associated with using BAFs but requires the sampling of appropriate prey biota for implementation.

The equation in the text box below used to develop a tissue-based WV is based on the GLI model for aquatic-dependent birds and mammals but expressed as the chemical concentration in the diet rather than in water (see USEPA (2005), Section 4.4). As discussed above, sources of exposure information can be found in USEPA (1993, 1995), Conder et al. (2020), and Divine et al. (2020).

Note that if the target aquatic-dependent wildlife is exposed via several trophic levels, a WV will need to be calculated for each trophic level using BAFs, or if available, applicable BMFs for the targeted aquatic-dependent wildlife receptor (see Section 5.6). This will then guide which species of prey/forage to target when monitoring for compliance.

Because this approach was developed to address the bioaccumulation of lipophilic chemicals, it assumes the chemical contribution from water is negligible, which, as discussed in Section 5.5.2, may not be the case for some PFAS. Furthermore, it does not consider dietary intake via the incidental ingestion of sediment, which as noted above, can be included depending on the species of wildlife being evaluated. As indicated by Larson, Conder, and Arblaster (2018), incidental sediment ingestion could be a significant contributor to exposure to aquatic-dependent wildlife.

Standard Equation for Derivation of a Protective Prey Tissue Value for Aquatic-Dependent Wildlife

$$\text{WVww (mg/kg food)} = \frac{\text{TD (mg/kg bw/d)} * (1/(\text{UF}_A * \text{UF}_S * \text{UF}_L))* \text{BW (kg)}}{\text{sum [FC}_i\text{ (kg food/d]}}$$

Where:

WVww = wildlife value expressed as the chemical concentration in the diet of each representative species measured as wet weight

TD = test dose expressed as daily dietary dose (wet weight) from selected study, either a NOAEL or a LOAEL

UF = uncertainty factors for interspecies variation (UF_A), subchronic to chronic (UF_S), and LOAEL to NOAEL (UF_L)

BW = body weight of a representative species

FC_i = amount of daily food consumed for each species from the i^{th} trophic level

16.4 Sampling and Analysis

This section reviews the collection and analysis of surface water, biota, and surface sediment from aquatic systems. In most instances, the precautions taken to minimize biasing the concentrations of PFAS in the samples from sampling equipment and/or sampler protective clothing, among others, are the same as those described in Section 11.1 when sampling groundwater, surface soils, or fish. There are some unique aspects about where to collect a surface water sample that are discussed in this section. For analysis, the methods used for PFAS in drinking water, soil samples, plant material, and groundwater described in Section 11.2 are also used for surface water, biota, and surface sediment. Issues and recommendations unique to sampling PFAS-containing foam are covered in Section 16.5.

16.4.1 Surface Water Sampling

Surface water bodies include, but are not limited to, oceans, bays, estuaries, lakes, streams, ponds, creeks, springs, wetlands, reservoirs, and artificial impoundments. The sample collection for PFAS from a surface water body is essentially the same as for other chemicals or pollutants. Standard operating procedures for sampling equipment have the same limitations, such as PFAS-free samplers, that are used for collection of samples from potable water systems or groundwater monitoring wells. See Section 11.1 for general sampling techniques and equipment requirements for PFAS sampling, including examples of PFAS-specific sampling protocols, and Section 11.2 for analytical methods and techniques.

In addition to USEPA's Compendium of Superfund Field Operations Methods (USEPA 1987) for general guidance on sampling surface water, Michigan (MI EGLE 2021; MI DEQ 2018) and New York (NY DEC 2021) have recently developed guidance specifically for PFAS. Some examples of sampling consideration in a moving water body such as a creek include:

- sampling far enough downstream from the suspected source to allow for adequate mixing
- collecting samples from the upstream side of the sampler to minimize compromising the sample
- collecting the sample from mid-depth in the thalweg (that is, along the natural direction of water flow, below the air/surface water interface but above the surface water/surface sediment interface)

- depending on your sampling objectives, collecting samples from multiple depths to provide the necessary information. This is due to the potential for stratification of PFAS concentrations through the water column and the location of the receptors of concern (benthic organisms or fish).

Due to chemical properties of PFAS, concentrations in the surface water near the discharge location may be higher at or near the surface. Collecting samples only from the surface may inform you of the worst-case scenario but may not provide information on locations away from the discharge point, such as at a water intake for domestic and industrial use. The same concern applies to PFAS-containing foam. Including this foam in the sample will bias the PFAS concentration high due to the elevated concentrations in the foam (see Section 16.5.5).

Additional considerations for surface water sampling during site characterization are noted below in Section 16.4.5.

16.4.2 Biota Sampling

Because some PFAS are known to accumulate in aquatic biota and in some instances may drive the development of surface water quality criteria (see Sections 16.2.2.2 and 16.3.3), sampling for biota may be an important component of a monitoring program or health assessment. The species of biota to collect and the tissue types to sample will depend on the study objectives. For example, a human health–based study should focus on collecting species within a size range targeted by recreational anglers or crabbers (NJDEP 2018), while an ecological-based study should focus on species representing different trophic levels, as well as benthic and pelagic habitats, and be of a size range targeted by piscivorous birds and mammals. In addition, because it has been shown that some PFAS bioaccumulate to a higher degree in the blood and liver compared to the flesh (see Section 11.1.7.8), collecting and analyzing different tissue types might be an important consideration in a study design.

General guidance on the use of different sampling techniques for fish and shellfish such as gill nets, seines, trawls, and electrofishing, can be found in USEPA (2000), and many states have their own guidance, which should be considered. When sampling biota for PFAS analysis, the additional precautions described in Section 11.1 should also be followed, and some states, such as Michigan, have developed their own PFAS-specific guidance (MI DEQ 2019). For example, collected biota should be wrapped in HDPE or polypropylene bags and/or aluminum foil, and stainless-steel tables, knives, and weighing scale hooks should be used for sample processing (in the field or in the lab), as well as untreated wooden cutting boards. Given that PFAS are widely present in the environment and human-made materials, it will be important to collect equipment blanks during sample collection and processing. Close coordination with the analytical laboratories will be needed to ensure similar PFAS-specific precautions are followed at all times (see Section 11.2).

Additional considerations include sampling surface water and surface sediment within the same area from which the biota are collected. While it is recognized that many aquatic biota are migratory or exhibit extended home ranges, this information will help support identification of PFAS sources as well as potentially the development of site-specific BCFs, BAFs, and biota-sediment concentration factors (BSAFs). BSAFs represent the amount of PFAS taken up by an organism from the sediment and are measured as the ratio of the concentration in an organism to the concentration in sediment. BSAFs are typically developed for those organisms in close contact with surface sediment, such as benthic and epibenthic invertebrates, as well as benthic fish (Figure 17-1).

16.4.3 Sediment Sampling

Because sediment can be a contaminant sink, a transport mechanism, and a source of contaminants to a surface water body and to benthic organisms, it may be necessary to sample sediment for PFAS to support an understanding of its contribution to the surface water quality and/or biota tissue concentrations. Conventional sediment sampling and coring techniques and protocols can generally be used to obtain samples for analysis of PFAS. Section 11.1 describes sampling protocols for all types of samples, with additional detail for porewater in Section 11.1.7.4 and sediment samples in Section 11.1.7.7

Examples of seven different sampling protocols typically used are detailed below:

- Where the sediment is accessible and can hold its form without collapsing, a corer or “Dormer Piston” sediment sampler could be used.
- When collecting samples from shore or wading, the sample should be collected from the upstream side of the sampler to minimize potentially compromising the sample from stirred-up sediment or from a waterproof coating on waders.
- Sediment core samples are collected directly from single-use liners and are not reused.
- There can be sites where the sediment is accessible but either the sediment is sloppy and would not hold its

form, or there is a high density of tree roots or boulders and a corer or piston sampler would not be feasible. In these situations, a stainless-steel trowel could be used to collect surface sediment samples.

- For subtidal sediments, the depth below the sediment surface from which the sample is required determines what equipment is needed. For surface sediment samples, devices such as a modified van Veen grab, Ekman grab, or Ponar grab sampler can be used, while for deeper subsurface samples, devices such as a vibracorer should be used. This nondedicated equipment (equipment used for more than one water body or location) should be verified as PFAS free, and the sampling program should include collection of equipment blanks.
- For sampling subtidal sediments, the depth from which the sample is required dictates what specialized sampling equipment is needed.
- Samples should be collected in HDPE wide-mouth bottles provided by the laboratory, and fitted with an unlined (no Teflon) polypropylene screw cap. A minimum of 50 g of sample is needed. Field observations, including sediment type, texture, and color, should be recorded.

16.4.4 Analytical Methods

Analytical methods for the analysis of PFAS in a surface water share many of the same components as those used for PFAS in other non-drinking water media. A discussion of these analytical methods is found in Section 11.2. Most surface water samples for PFAS are analyzed by Modified USEPA 537.1 and use the DOD’s Quality Systems Manual (QSM) for Environmental Laboratories, Version 5.3, Appendix B, table B-15 (USDOD 2019), providing the most current and comprehensive set of quality standards for PFAS analysis. In June 2019, USEPA validated USEPA SW-846 Method 8327 for the analysis of PFAS in surface water, groundwater, and wastewater (USEPA 2021). Method 8327 is available for use but has not yet been fully incorporated into SW-846. Method 8327 has not been widely used because it creates laboratory cleanup and accuracy issues and is not accepted by DOD.

16.4.5 Site Characterization

Conducting site characterization of PFAS at a site with a surface water body should begin with determining the beneficial uses as described in Section 16.1.1. Those beneficial uses should be used to select the types of samples to be collected. For example, if evaluating PFAS-containing foam, sample collection will be required near the surface; if evaluating potential impacts to benthic organisms, samples closer to the sediment/water interface should be collected, and if evaluating pelagic fish, it may be necessary to collect a surface water sample integrated throughout the water column. Point sources such as stormwater discharge pipes or a publicly owned treatment works (POTW)discharge should be located and potentially targeted for sampling to evaluate sources of PFAS to the water body. Establishing the locations of natural and human-made water inflow and outflow points to the water body will also help guide sample points and potential exposure sites. Groundwater/surface water interaction may also play a role in establishing the conceptual site model and locating places to sample. Section 10 contains more specifics regarding site characterization and development of a conceptual site model.

16.5 Surface Water Foam

PFAS-containing foam (discussed in this section) is differentiated from AFFF (discussed in Section 3) in that it is the result of dissolved-phase PFAS in surface waters that have been agitated by wind or wave action and aggregated into a mass at or above the surface of the water, irrespective of the PFAS source type. As noted in Section 16.2.2.4, the presence of foam does not necessarily indicate the presence of PFAS. Foam can form naturally when the surface tension of water decreases and the concentration of organic matter, such as dissolved organic carbon (DOC), increases and is mixed into the water. The decomposition of organic material into water, or a storm event mobilizing existing organic material, can lead to the natural formation of foam on surface water. For example, a study of PFAS and DOC in foam forming on a freshwater lake in Michigan showed that PFAS made up less than 0.1% of the DOC present in the foam samples, which indicated that DOC was the primary cause of the foam and not the presence of PFAS (Schwichtenberg et al. 2020).

This section discusses the formation of PFAS-containing foam, the characteristics of, and stratification within the foam, a brief discussion of analytical methods for foam, and the enrichment of PFAS concentrations in foam compared to the underlying water column. A case study on PFAS containing foam (the Minnesota Project 1007 Feasibility Study) is presented in Section 15.5.1.

16.5.1 Foam Above Water Interface

PFAS-containing foam may occur at and above the air-water interface on surface waters. In this context, surface water is subdivided and defined below. This subdivision describes vertically downward the air-water interface, surface micro layer (SML), neuston, and underlying water column. See Figure 16-2.

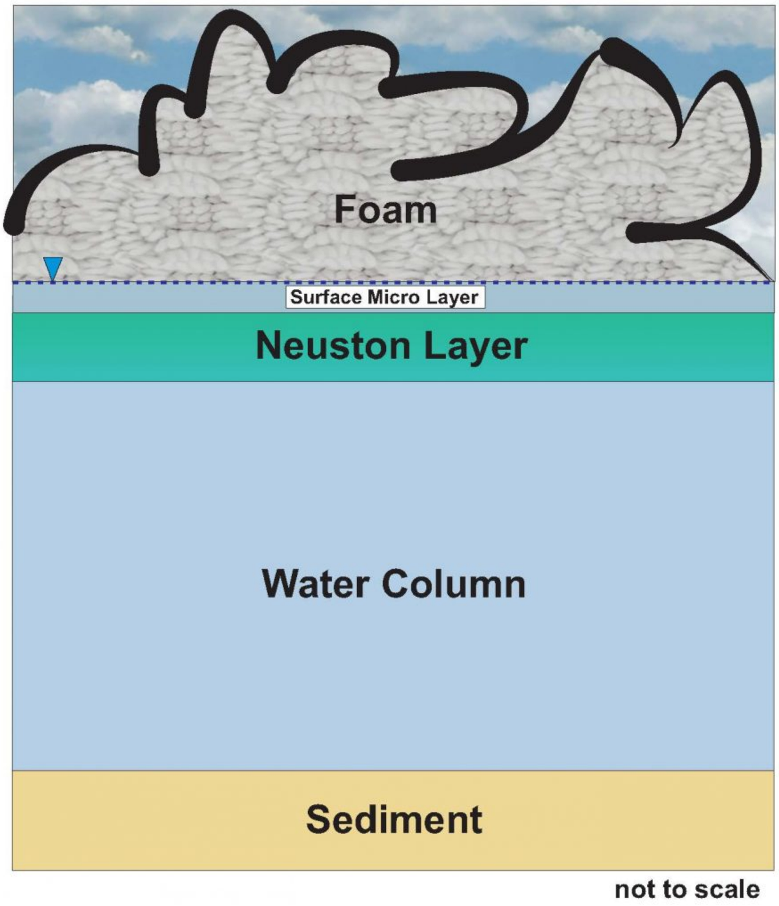


Figure 16-2. PFAS foam on surface water

Although it is typical to find PFAS-containing foam near release source areas, it may also occur some distance away when surface water bodies are interconnected. Source proximity may impact the concentration of PFAS analytes in the foam column itself. However, concentrated PFAS-containing foam may occur on surface water bodies containing low to nondetect PFAS concentrations immediately below the foam itself some distance from the source areas (MPCA 2020; Schwichtenberg et al. 2020). Underlying partitioning considerations are discussed in Section 5.2.2, Considerations for PFAS Partitioning.

Variable surface water depth, flow conditions, and co-contaminant mixtures may affect the presence, aggregation, and physical movement of PFAS-containing foam in the SML and above the air-water interface. These factors may be considered when evaluating fate and transport of PFAS-containing foam, as it may partition back into solution in the water column as it moves with the flowing water. A foam column at and above the surface may be affected by physical forces, including precipitation, wind, and wave action, causing it to separate and travel as smaller foam source material “islands” or collapse and dissolve back into the water column as it travels with the wind and waves.

16.5.2 Foam Characteristics

PFAS-containing foam has wide-ranging visual and textural appearances. These characteristics range from deflated, dry, or aged in appearance, as small aggregations of bubbles accumulating into larger islands of billowed piles, frozen in standard bubble foam appearance or frozen in thin sheetlike membrane appearance, frozen on top of snow and ice, dark coloration due to detritus or organic content, and bright white, with an aerated shaving cream or whipped cream texture.

“High turbulence generated foam tends to be fluffy, actively regenerates, and does not appear to contain high levels of organic material; while older, deflated foam does not actively regenerate and appears to be rich in organic or non-organic particulates. Foam observed along creeks and streams tend to vary in appearance and can occur with any combination of the above-listed characteristics. Wind-generated foam has only been observed on lakes, has generally been white and fluffy, and has actively accumulated along a downwind shoreline. Both organic-rich foam and unfrozen foam with a wrinkled appearance have been observed to accumulate along ice dams or ice shelves" (MPCA 2020).

16.5.3 Stratification Within Foam

Surface water foam is known to be laden with bacteria, detritus, and other naturally occurring material. However, stratification of concentrations of PFAS within the foam column or pile may be due to a number of physical and chemical conditions. For example, co-contaminants may impact the degree of stratification in the surface water column and the foam itself. Additionally, the foam may be aged and in a dry condition toward the top of the foam column/pile, creating a concentration gradient toward the base of the column/pile.

Sampling should be conducted so as to maximize consistency and reproducibility during PFAS surface water sampling to understand PFAS stratification in the surface water column and the foam. The Michigan Department of Environment, Great Lakes, and Energy (EGLE) has published a surface water foam sampling guidance, a surface water foam study report, and has published other PFAS sampling guidance (MI EGLE 2019, 2021, 2021).

As of the date of this publication, the state of Minnesota is working with technical support from the USEPA Office of Research and Development to evaluate foam sampling techniques aimed at understanding the concentration variability within the foam, at the surface micro layer, and the underlying near-surface water column.

16.5.4 Frozen Foam

PFAS-containing foam has been confirmed in frozen form on surface water in Minnesota, Michigan, and Wisconsin (MPCA 2019). Appearance of the foam is difficult to distinguish from snow and ice along stream or lake embankments. PFAS-containing ice has been confirmed in Michigan and can visually take the form of thin film-type islands or within massive ice (MPCA 2020). The ice appears to stratify vertically in concentration where located in massive ice. Confirmation of the degree of stratification in massive ice is an on-going study at this time. Early results from Michigan indicate it appears to increase in concentration with elevation in the ice cores, indicating the ice/air interface may be where the highest concentrations exist, similar to the propensity for PFAS to travel at the air/water interface.

16.5.5 Surface Micro Layer

As previously discussed, PFAS in solution tends to accumulate at the air/water interface, also known as the surface water micro layer or SML. The SML in this context, is generally understood to mean the layer in contact with ambient air and is approximately 50µm thick (MPCA 2020). Variability in sample collection techniques and the extent to which this interface is included or omitted in the collection of a bulk water sample may result in biased analytical results. This can further lead to incorrect conclusions about PFAS concentrations in surface waters at source areas and in the downgradient direction. Where the SML is not characterized and only the deeper water column is sampled, PFAS concentrations may be biased low . The SML may be the location of the highest PFAS concentration in the water column. Omitting collection of the SML could potentially lead to an inaccurate assessment of the risk to human and ecological receptors. Therefore, when preparing a sampling plan, it is important to consider the depth of the water column that is most relevant to the human and ecological receptors that may be exposed to PFAS; different receptors may require unique sampling strategies. At this time, methods to characterize PFAS concentrations and the nature of exposed biota in the SML are still under study (see SERDP project ER19-1205, Field et al. 2021).

Due to the physical and chemical properties of PFAAs, including their hydrophilic heads and hydrophobic tails, a given molecule may preferentially exist within the SML. Section 4 includes information about PFAS physical and chemical properties. Sampling the SML in relative isolation from the neuston layer below it or the foam column above it may become an important factor in accurate representation of the concentrations emanating from the SML into foam above when physical agitation occurs. The Michigan EGLE guidance for sampling PFAS-containing foam provides a starting point to understanding the considerations of this sampling protocol in varied circumstances (MI EGLE 2019). Michigan EGLE has also published other PFAS sampling guidance that may be relevant for a project (MI EGLE 2021).

16.5.6 Neuston Layer

The neuston layer may be defined, for the purposes of studying PFAS-containing foam, as the zone directly underlying the SML that is typically enriched with biological life and aligns with the larger definition by Wurl et al. (2017), which was related to strata thicknesses. Wurl et al. (2017) indicated:

> "The sea surface microlayer is the boundary interface between the atmosphere and ocean, covering about 70% of the Earth's surface. The SML has physicochemical and biological properties that are measurably distinct from underlying

> waters. Because of its unique position at the air-sea interface, the SML is central to a range of global biogeochemical and climate-related processes. Historically, the SML has been summarized as being a microhabitat comprised of several layers distinguished by their ecological, chemical and physical properties with an operational total thickness of between 1 and 1000 µm."
>
> "While this 1,000 µm SML definition is large enough to encompass the neuston, the refined definition of 50 µm thick SML provided above is considered the state-of-the practice for the purposes of understanding and evaluating PFAS-containing foam and layers of significance immediately underlying it. Liss and Duce (1997) clarify the neuston below the 50 µm SML as two distinct biological layers, "[The] neuston can be divided into epineuston and hyponeuston. The epineuston includes more than 40 species of water striders, *Halobates*, inhabiting the open ocean and coastal areas. The hyponeuston are organisms in the surface centilayer including hydrozoa, mollusks, copepods, isopods, decapod crustaceans, fishes, and the seaweed *Sargassum*."

Section 11.1.7.3 includes generalized surface water sampling guidance references. For PFAS-containing foam on surface water, it appears that the neuston layer is of particular importance in understanding dissolved-phase PFAS within the water column that may be available to the SML for aggregation and concentration into foam at the air-water interface. The neuston may also provide insight into the stratification of PFAS in the water column below the interface.

16.5.7 Analytical Methods

Analytical methods for the analysis of PFAS-containing foam are essentially the same as those used for PFAS in other non-drinking water media. A discussion of these analytical methods is found in Section 11.2. As with all non-drinking water samples, there is no USEPA-certified method for the analysis of PFAS at the time of this publication. Efforts are being undertaken to develop the various analytical methods for the various non-drinking water media. Since there may be very high levels of PFAS in PFAS-containing foam, the laboratory should be warned of this potential so that it can take the necessary precautions during analysis. In the Minnesota case study (MPCA 2020), a commercial laboratory analyzed PFAS-containing foams using their proprietary method of LC/MS/MS. These foam samples were collected following the Michigan foam sampling guidance noted above, with caution taken to prevent dilution of the sample by minimizing contact with the water during foam sample collection.

16.5.8 Enrichment Factors

Enrichment factors are defined for the context of this document as "the calculated fold increase (or decrease) of PFAS concentrations in foam compared to the co-located surface water sample. These values are unitless and are determined by dividing the foam concentration of a specific PFAS compound by the concentration of the same compound detected in the surface water sample. The foam enrichment factor for a given PFAS compound indicates whether that compound is preferentially concentrating into the foam from the bulk water column" (MPCA 2020).

As reported by McMurdo et al. (2008), "Kaiser et al. (2006) observed that surface foam created by bubbling air through an aqueous solution was enriched in perfluorooctanoate PFO by up to 3.2 times." However, simple enrichment factors have been documented in PFAS analytical samples from sites in Minnesota with factors ranging up to >32,000 times (MPCA 2020).

Currently, the extent to which the presence of foam may deplete PFAS concentrations in surface water is unclear. Enrichment factors of short-chain versus long-chain PFAS differed in one Minnesota case study (MPCA 2020) where 33 PFAS analytes were provided. With few exceptions, "short chain PFAS did not tend to enrich into the foam. Often the four, five, and six-carbon length chains were not detected in the foam samples. If they were detected, their concentrations were lower compared to concentrations measured in the surface water sample. Long-chain PFAS were found to have relatively higher foam-to-water enrichment factors than short chain PFAS. In a majority of the samples, 2-(N-ethyl-perfluorooctane sulfonamide) acetic acid (ETFOSAA) and perfluorooctanesulfonamide (PFOSA) had the largest foam enrichment" (MPCA 2020).

The ability of surfactants to concentrate in surface water foam is well known, but may be particularly of interest near source areas due to the ability of PFOA to partition into air circumstantially. Both terminal PFOA and PFOS may become entrained in these foams at high concentration, posing particular risk to ecological receptors in the neuston, SML, and those species reliant on the biological life above and below these zones. In support of this notion, Battelle (2018) indicated, "Foams in the natural environment are metastable and generally dissipate within seconds to days. Compositionally, foams are very similar to the SML, they are formed from the air entrapment on SML and they destabilize back to form SML. Compared to bulk water, foams are significantly enriched in many dissolved and particulate components, including particulate and organic matter, clay minerals, lipids, hydrocarbons, proteins, bacteria, hydrophobic contaminants, and heavy metals. As such, foams can provide a mechanism for fast transport of the contaminants through aquatic systems and a potential exposure pathway for aquatic animals and humans." Due to concerns over potential adverse health effects from exposure to PFAS containing foam, the Michigan Department of Health and Human Services (MDHHS) recently issued a recommendation advising residents and visitors to avoid foam on Michigan waterbodies (MPART 2023).

16.6 Effluent Limits for PFAS

This section provides information about the current status of effluent limits for PFAS from discharges of wastewater to surface water.

16.6.1 Introduction

The protection of surface water quality from the impacts of discharges from publicly owned treatment works (POTWs) and industrial wastewater treatment works is based on the establishment of effluent limits for pollutants in the discharges from those facilities. The effluent limits are enforced through National Pollution Discharge Elimination System (NPDES) permits. Those effluent limits are developed by establishing technology-based (TBELs) and water quality-based (WQBELs) effluent limits for a specific pollutant and using the most restrictive value of the two for the final effluent limit in the permit.

Effluent limits are also informed by effluent limit guidelines (ELGs) that are national wastewater discharge standards developed by USEPA on an industry-by-industry basis. These are technology-based regulations that are intended to represent the greatest pollution reductions that are economically achievable for an industry. The standards for direct dischargers are incorporated into NPDES permits issued by states and USEPA regional offices and permits or other control mechanisms for indirect dischargers (https://www.epa.gov/eg/learn-about-effluent-guidelines).

As of the date of this document, there are no USEPA-established ELGs for PFAS. USEPA outlined an approach for establishing ELGs for select PFAS in its PFAS Strategic Roadmap (USEPA 2021) and the agency released its Effluent Guidelines Program Plan 15 in 2023 (USEPA 2023 (see Section 16.6.5). Currently, only North Carolina has an NPDES permit with TBELs for PFAS. These TBELs were established using Best Professional Judgment, (USEPA 2010), the process used when ELGs are not available. Minnesota has adopted an NPDES permit with WQBELs for PFOS (see Section 16.6.4.1).

16.6.2 ELG Development and Implementation

This section summarizes the state of practice for how technology-based ELGs are developed and used in the process for selecting NPDES permit effluent limits. This is followed by a discussion of the current state of knowledge regarding data collection and ELG development plans by USEPA for PFAS.

16.6.2.1 ELG Development

ELGs "represent the greatest pollutant reductions that are economically achievable for an industry" (USEPA 2021[2432]). ELGs for direct discharges to surface water are enforced through effluent limits established in NPDES permits issued by state and USEPA regional offices. For discharges to a POTW, the ELGs are enforced through a pretreatment program established by the POTW and enforced through its NPDES permit and the permits issued by the POTW for discharges into its collection system. For the process of using ELGs to develop TBELs for an NPDES permit, see section 5.2.1 of the Permit Writer's Manual developed by USEPA (2010).

ELGs are developed from empirical data that represent the performance of various technologies and best management practices available to any given industry type (See Figure 16-3 for key steps in the process). For toxic and nonconventional pollutants such as PFAS, ELGs are developed based on Best Available Technology Economically Achievable (BAT) (USEPA 2010). The ELG based on BAT is established using the performance associated with the best control and treatment measures that facilities in an industrial category can achieve while also taking into consideration economic achievability as it relates to pollutant reduction benefits. Many other factors are also considered in establishing the ELG and not just for those based on BAT. These factors can either be numeric or non-numeric/narrative limitations based on use of a specific best management practice (BMP). For more information, see section 5.2.1.1 of the Permit Writer's Manual (USEPA 2010).

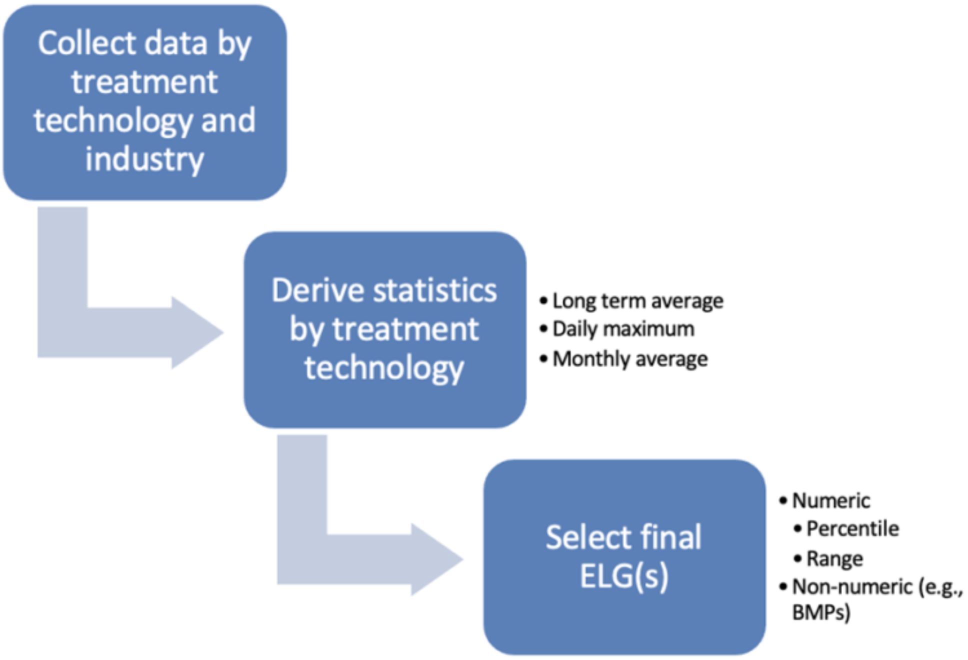
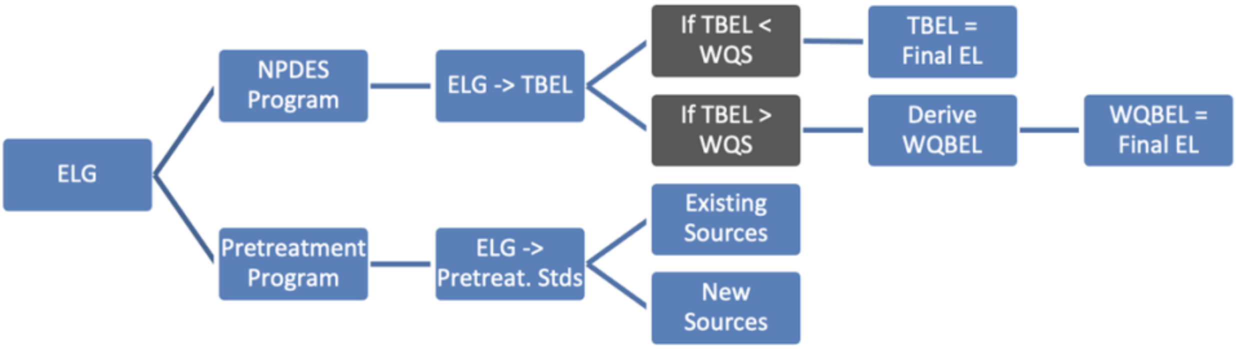


Figure 16-3. Key steps in the process of ELG development.

16.6.3 ELG Implementation

During the development of an NPDES permit, if it is found that the ELGs and/or state-established TBELs will not be sufficiently protective of water quality in the receiving water, then the CWA requires the development of WQBELs. WQBELs are developed so that the discharge authorized by the permit will not cause an exceedance of water quality standards that protect designated beneficial uses of the receiving water. See Section 16.1 for a discussion of beneficial uses for receiving waters. Some of the common beneficial uses include as drinking water, aquatic habitat, contact and non-contact recreation, and for commercial and sport fishing. Besides beneficial uses, the WQBELs take into account information about the receiving water that includes attributes such as ambient water quality, flow, dilution and additional discharges. For a comprehensive look at the WQBEL process, see Chapter 6 of the Permit Writer’s Manual (USEPA 2010).

In summary, the implementation of ELGs depends on whether the permit is for “direct discharge” (a direct discharge from the facility to ambient surface water) or “indirect discharge” to a POTW and permitted via a pretreatment program (Figure 16-4). For direct discharges, the ELG is typically used to set the TBEL, which is then compared against the ambient water quality standard (WQS) to see if it can be achieved by the TBEL alone. If implementing a TBEL would not lead to an exceedance of the WQS, then the TBEL could be used to set the final effluent limitation, after consideration of site-specific factors. If the TBEL might lead to a WQS exceedance, then development of a WQBEL is typically required for setting the final effluent limitation. WQBELs must consider not only federal requirements but any state-specific requirements. Note that for PFAS, only a few states have WQS (see the Water and Soil Regulatory and Guidance Values Table), so the availability of standards for use in setting WQBELs is as yet limited. As noted in Section 16.1, USEPA has published draft national recommended aquatic life criteria for PFOA and PFOS in freshwater (USEPA 2022; USEPA 2022). USEPA also plans to develop ambient water quality criteria for the protection of human health (based on drinking water and fish consumption) by Fall 2024. For more information on the potential risks to human health and ecological receptors from exposure to PFAS, see Section 9.1 and 9.2, respectively. For indirect discharges, pretreatment standards are selected from ELGs for existing sources, and for new sources.



- ELG = Effluent limit guideline (national technology-based discharge standards)
- TBEL = Technology-based effluent limit (minimum technologically achievable limit)
- WQBEL = Water quality–based effluent limit (limit needed to meet risk-based WQS instream)
- Final EL = Final effluent limit (allowable effluent discharge that meets WQS instream)
- WQS = Water quality standard (ambient, risk-based, for protection of aquatic life, human health, etc.)

Figure 16-4. Schematic for implementation of ELGs

16.6.4 Status of ELGs and Effluent Limitations for PFAS

16.6.4.1 Existing ELGs and Effluent Limitations for PFAS

At the date of publication of this document, USEPA has not been established ELGs for PFAS. Therefore, while USEPA is in the process of developing ELGs and water quality criteria for PFAS, the agency released a memorandum in 2022 recommending that states develop permit-specific effluent limitations for PFAS based on TBELs (USEPA 2022[2650]). This was the approach taken by North Carolina in issuing an NPDES permit for the discharge of treated water from a groundwater remediation project (NC DWR 2022[2431] (see text box below). The PFAS limits developed for this NPDES permit are considered TBELs, unique for this discharge, and should not be assumed protective for a different NPDES permit.

Minnesota has issued an NPDES permit for a municipal wastewater treatment facility with effluent limitations for PFOS based on Minnesota's water quality standard for PFOS (MPCA 2022). The treatment facility discharges to a river. The effluent limitations for the permit, which are a daily maximum of 497 ng/L and a quarterly average of 287 ng/L, were developed based on a reasonable potential analysis. That analysis indicated a reasonable potential for exceedance of Minnesota's water quality standard of 12 ng/L PFOS for a river. As the facility is undergoing an expansion, the limits are enforceable upon completion and startup of the expansion, but no later than 6 months prior to permit expiration. The 2013 permit also contains a limit on the mass loading of PFOS in biosolids applied by land application of 0.384 lbs/acre. This limit is not found in subsequent permit updates in 2018 and 2022. These values were developed on a site-specific basis and are not necessarily protective for a different discharge.

North Carolina NPDES Permit for a Groundwater Remediation Discharge

Problem: PFAS in groundwater discharging to river—60% of PFAS load to river.

Solution: Capture groundwater seeps to river and treat to remove PFAS.
Primary indicator PFAS – HFPO-DA (GenX); PFMOAA (perfluoro-2-methoxyacetic acid); PMPA (perfluoromethoxypropyl carboxylic acid). Sufficient reduction of these shown to be indicative of sufficient reduction of total PFAS in discharge.
Discharger provided evaluation showing that granular activated carbon (GAC) could remove the 68 PFAS listed in the permit by at least 99%. **Established as the TBEL**.
Effluent limitation set at 99% reduction on a monthly mass basis using the three indicator PFAS to show compliance.
Based on current concentrations—the expected effluent would be less than 122 ng/L HFPO-DA, 643 ng/L PFMOAA, and 132 ng/L PMPA.
When USEPA adopts PFAS surface water quality criteria, a reasonable potential analysis will be conducted and the permit will be reopened to include new effluent limits based

16.6.4.2 USEPA PFAS Data Collection for ELG Development

USEPA's collection of data to support development of on water quality if they are more stringent than the TBEL.

ELGs for PFAS has been primarily through its effluent guideline program plans (specifically Plans 14 and 15), a 2021 Advance Notice of Proposed Rulemaking (ANPRM), and a 2021 Multi-Industry PFAS Study. In addition, USEPA is collecting data from landfills to support possible development of PFAS effluent limits for landfill leachate, and from industrial discharges to POTWs for possible development of PFAS pre-treatment effluent limits. These activities are discussed below.

USEPA Effluent Guidelines Program Plan 14

In 2019, USEPA issued its Preliminary Effluent Guidelines Program Plan 14 (Preliminary Plan 14) (USEPA 2019) and a supporting report, The USEPA's Review of Per- and Polyfluoralkyl Substances (PFAS) in Industrial Wastewater Discharge (USEPA 2019). The preliminary plan and the report discussed an initial review of PFAS discharges to surface waters and POTWs and concluded that "…little is known about the identity, frequency, or amount of PFAS compounds discharged in industrial wastewater." The report recommended a follow-up study to collect data on PFAS manufacture, use, control, and discharge to surface water by industries USEPA determined to be likely dischargers of PFAS. These consisted of airports, organic chemical manufacturers, paper and paperboard manufacturers, and textile and carpet manufacturers. This became the Multi-Industry PFAS Study (see below). With publication of the final Plan 14 in 2021 (USEPA 2021), metal finishers were added to the Multi-Industry PFAS Study.

Advance Notice of Proposed Rulemaking

In March 2021, USEPA issued an Advance Notice of Proposed Rulemaking (ANPRM) titled "Clean Water Act Effluent Limitations Guidelines and Standards for the Organic Chemicals, Plastics and Synthetic Fibers Point Source Category" (USEPA 2021). The ANPRM noted that USEPA was "initiating further data collection and analysis to support potential future rulemaking under the CWA relating to ELGs, pretreatment standards, and new source performance standards applicable to the OCPSF point source category."

Multi-Industry PFAS Study

As an outcome of USEPA's effluent guideline program, The Multi-Industry PFAS Study (USEPA 2021) focused on collecting, compiling, and reviewing information and data on PFAS in discharges from industries in the following point source categories:

- Organic chemicals, plastics and synthetic fibers (OCPSF) manufacturers and formulators
- Metal finishing
- Pulp, paper, and paperboard manufacturers
- Textile mills
- Commercial airports (excludes USDOD facilities)

In addition, the study also attempted to acquire information on the types and concentrations of PFAS discharged in wastewater, as well as assess availability and feasibility of control practices and treatment technologies capable of reducing or eliminating PFAS in wastewater discharges. The information was collected through outreach to stakeholders, including company representatives and trade associations; state, regional, and local wastewater regulatory authorities; and treatment technology vendors. Data sources included 2019 and 2020 NPDES DMRs, USEPA's Industrial Wastewater Treatment Technology Database, USEPA's drinking water treatability database, and data made available through other federal agencies such as Department of Transportation, Federal Aviation Administration, Department of Health and Human Services, and Food and Drug Administration, and organizations such as the American Chemistry Council. The report includes detailed information on data sources, and whether any PFAS ELGs have been developed for industries within each of the point source categories.

USEPA Effluent Guidelines Program Plan 15

USEPA discussed its findings from the Multi-Industry PFAS Study and its plans to develop ELGs for PFAS in the 2021 Preliminary Effluent Guidelines Program Plan 15 (USEPA 2021) and the subsequent 2023 Effluent Guidelines Program Plan 15 (Plan 15) (USEPA 2023). A summary is provided below.

OCPSF Manufacturers and Formulators

In December 2021, USEPA used its authority under Section 308 of the CWA to collect data on characterization of wastewater generation, treatment, and discharge from PFAS manufacturing facilities. USEPA "verified that PFAS, including legacy long-chain PFAS and short-chain replacement PFAS, are present in wastewater discharges from OCPSF facilities" (USEPA 2021) to surface waters and POTWs. For both PFAS manufacturers and formulators, average concentrations of short-chain perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkane sulfonic acids (PFSAs) were generally higher relative to long-chain PFCAs and PFSAs. USEPA determined that the development of ELGs for PFAS manufacturers is warranted and plans to revise the existing OCPSF ELGs (40 CFR Part 414). As noted in Program Plan 15, depending on available resources, USEPA intends to publish a proposed rule in spring 2024. In addition, USEPA will continue to evaluate the need to develop regulations to address PFAS discharges from PFAS formulators/processors.

Metal Finishing

USEPA determined that PFAS have, and continue to be, used by metal finishing facilities in the United States. USEPA identified chromium electroplating facilities as the most significant source of PFAS due to their use of PFAS-based mist/fume suppressants to control toxic hexavalent chromium emissions. USEPA determined that the development of effluent guidelines and standards for chromium electroplating facilities is warranted and plans to revise the existing metal finishing ELGs (40 CFR Part 433). Depending on the availability of resources, USEPA intends to collect the data necessary to revise these ELGs, which will include conducting a survey of the industry and analysis of wastewater samples. According to the finalized Program Plan 15, USEPA intends to publish a proposed rule by the end of 2024.

Pulp, Paper, and Paperboard

While USEPA determined that PFAS have been and continue to be used by U.S. pulp, paper, and paperboard facilities, only a small subset of facilities are actively applying PFAS to paper products. The information collected by USEPA indicates that the industry phased out the use of PFOA and PFOS approximately a decade ago but continues to use FDA-approved short-chain PFAS in limited quantities for the manufacture of food contact packaging and specialty paper products. The industry is expected to transition to PFAS-free technologies and eliminate all application of PFAS in U.S. pulp and papermaking operations by 2024. This schedule coincides with an FDA agreement with chemical manufacturers to voluntarily phase out use of PFAS that contain or may degrade to 6:2 fluorotelomer alcohol (6:2 FTOH) in food contact applications by 2024. As a result, a rulemaking on the pulp, paper, and paperboard category is not a priority for USEPA at this time. USEPA plans to continue to study this point-source category, paying particular attention to the potential for legacy discharges after the transition to PFAS-free additives.

Textile and Carpet Manufacturers

As reported in Preliminary Plan 15 (USEPA 2023), much of the information on textile and carpet manufacturers obtained was through a review of publicly available information and literature. Based on a small number of sample results, USEPA determined that PFAS, including legacy long-chain PFAS, are present in wastewater discharges from textile mills to POTWs and that most textile mills were not monitoring for PFAS. Subsequently in November 2021, USEPA used its authority under Section 308 of the CWA to require nine textile manufacturers to provide information on PFAS use and import, PFAS in industrial wastewater discharges, and treatment of PFAS-containing wastewater. Nineteen of 92 (21 percent) reported they used PFAS in 2020, and of those, 18 of the 19 (95 percent) indicated their intention to reduce or eliminate use of PFAS by the end of 2026 by using alternative surface treatment products or technologies. More than half of the textile mills that responded to the survey discharge their process water to a POTW. Two indicated they operate a wastewater treatment system that can effectively remove or eliminate PFAS in wastewater. USEPA plans to expand its study of this category through use of a mandatory, nationally representative questionnaire.

Commercial Airports

USEPA determined that commercial airports may generate PFAS-containing wastewater from live-fire firefighting training, emergency response activities, and accidental leaks from stockpiles of AFFF. However, one outcome of the Federal Aviation Administration (FAA) Reauthorization Act of 2018 was that the FAA has approved and encourages use of different types of AFFF testing equipment that do not require dispensing AFFF when airports conduct periodic equipment testing and training. As of March 2022, the FAA has approved and is funding the use of four different types of firefighting testing devices that do not dispense AFFF and more than half of certified airports have applied these procedures. In addition, as of June 2022, all firefighting foam formulations that meet current military specifications contain less than 800 ppb of PFOS or 800 ppb PFOA. Based on this information, USEPA is not prioritizing rulemaking for this category at this time. However, USEPA will continue to study commercial airport use of AFFF that contains PFAS and will continue to monitor the industry's transition to fluorine-free foam (see Section 3.11 for more information).

Landfills
Based on public comments to Preliminary Plan 14, USEPA initiated a Landfill Leachate Detailed Study of wastewater discharges from landfills with a focus on PFAS discharges to surface waters and POTWs. Program Plan 15 notes that since September 2021, USEPA has collected data and information on the industry’s facilities, discharge practices, and effectiveness of control practices/technologies to remove PFAS. Depending on available resources, USEPA intends to revise the existing Landfills Point Source Category ELG to address PFAS (schedule yet to be determined).

POTW Influent Study
As noted in Program Plan 15, USEPA intends to collaborate with wastewater treatment facilities to initiate a nationwide study on industrial discharges of PFAS to POTWs. This includes indirect discharges from industrial categories that have been reviewed, as well new categories for which there are very little PFAS data. The goal is to collect samples of PFAS from industrial sources upstream of POTWs (that is, before mixing and dilution from other waste streams). USEPA also intends to develop an Information Collection Request (ICR) and a sampling strategy providing more details about the POTW Influent PFAS Study.

16.7 Surface Water/Groundwater Interaction

As mentioned in Section 16.4.5, surface water/groundwater interaction may play a role in a conceptual site model and locating places to sample. It has been found that PFAS in groundwater that migrates to surface water can be a significant source of PFAS in the surface water, potentially impacting beneficial uses. The same can be said for PFAS in surface water migrating and impacting groundwater quality. These concepts are demonstrated by a case study presented in Section 15.5.2 which describes two examples, one from North Carolina and one from Minnesota. Also see Section 5.3.4.1 for information on the fate and transport of PFAS due to groundwater/surface water interactions and Section 5.3.4.2 for information on surface water/sediment interactions.

Updated September 2023.

17 Additional Information

This section provides supplemental information for Section 6 on media-specific occurrence, Section 7.1 for human health effects, and for Section 9 on site risk assessment.

17.1 Additional Information for Media-Specific Occurrence

This section includes links for the tables of media-specific occurrence information that are summarized in Section 6 and included in the figures in that section.

- Tables 17-1 A-C – outdoor air, indoor air, settled dust, precipitation
- Tables 17-2 A-C – soil, sediment, and biosolids

The Section 6 interactive plots webpage provides additional information for the data included in the figures. The interactive figures were developed using R software and plotly.

The previous version of Section 6 (June 2022) is archived as a PDF under Archived External Tables and Sections on the home page of this site. The previous version of Section 17.1 (June 2022) is archived as a PDF under Archived External Tables and Sections on the home page of this site.

Table numbers 17-3, 17-4, and 17-5 are reserved for future updates in media-specific occurrence.

17.2 Additional Information for Human Health Effects

This section supplements information provided in Section 7.1 on biomonitoring, exposure, toxicokinetic, toxicology, and epidemiology data for long-chain and short-chain PFAAs. The PFAS discussed in Sections 17.2.3 and 17.2.4 include perfluorocarboxylic acids (PFCAs) with four to fourteen carbons and perfluorosulfonic acids (PFSAs) with four or more carbons. Also covered are two per- or polyfluorinated ether carboxylates (FECAs)—ammonium 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propanoate (also known as perfluoro-2-propoxypropanoic acid (PFPrOPrA); hexafluoropropylene oxide [HFPO] dimer acid, commonly known as GenX) (Section 2.2.3.5); and 4,8-dioxa-3H-perfluorononanoate (commonly known as ADONA); and per- and polyfluoroether carboxylates (PFECAs); per- and polyfluoropolyether carboxylates (PFPECAs) including chlorinated PFPECAs (ClPFPECAs); per- and polyfluoroether sulfonates (PFESAs) including chlorinated PFESAs; per- and polyfluoropolyether sulfonates (PFPESAs), fluorotelomer alcohols, and fluorotelomer sulfonic acids. These PFAS that contain ether group(s) are replacements for PFOA, PFNA, and/or PFOS as processing aids in certain fluoropolymer production, and some are also formed as industrial byproducts. They are included because they are of current interest and health effects data are available. There is little or no publicly available health effects information for most of the many other PFAS used in commerce (Section 2.5), including precursors that can be converted to PFAAs in the environment and in the human body.

For further detail of scientific names and carbon chain length of PFAAs see Section 2.2.

17.2.1 Overview

Based on the number of studies located through searches of the National Library of Medicine's PubMed, a database containing relevant peer-reviewed publications, much of the information summarized here became available after 2005. Additional studies may be available, particularly for those compounds with large health effects data sets, and additional information on the topics in this section can be found in databases such as PubMed and references listed in Section 7.1.

The publicly available toxicological data set is currently largest for PFOA and PFOS, with considerable data also available for PFBA, PFBS, PFHxA, PFNA, PFDA, and GenX. Fewer studies are available for PFHxS, PFUnA, PFDoA, ADONA, and the other ether and polyether PFAS mentioned above, and little or no data for PFPeA, PFHpA, PFTrA, PFTA, PFPeS, PFHpS, PFNS, or PFDS. Most of the mammalian studies were conducted in rodents, with a few in nonhuman primates (monkeys). The most notable toxicological effects from the mammalian studies of these PFAS, with relevant citations, are discussed in Section 17.2.5 and are summarized in Table 17-8 Toxicological Effects Excel file (last updated November 2021). However, due to the large size of the toxicological data set, it is beyond the scope of this section to identify no observed adverse effect levels (NOAELs) and lowest observed adverse effect levels (LOAELs) for these effects. The numerous reviews of potential epidemiological associations of health endpoints with PFAAs are discussed in Section 17.2.4. Many of the epidemiology studies evaluate associations of health endpoints with multiple PFAAs detected in the blood serum of the subjects. Epidemiologic data from the general population have been used to develop draft reference doses for PFOA and PFOS (CA OEHHA 2023; USEPA 2023), as well as for PFHxS and PFDA (USEPA 2023), and draft cancer slope factors for PFOA (USEPA 2023; CA OEHHA 2023) based on human data.

Finally, data gaps and research needs are discussed.

17.2.2 Human Biomonitoring and Sources of Exposure

Several long-chain PFAAs (from highest to lowest geometric mean [GM] serum levels, as follows: PFOS, PFOA, PFHxS, PFNA) are present in the low parts per billion (ng/ml) range in the blood serum of almost all adult residents of the United States, while other PFAS are detected in a smaller percentage of the population (CDC 2022; Olsen et al. 2017)). In contrast, short-chain PFAAs such as PFBS and PFHxA are more rapidly excreted and were infrequently detected in the blood serum of the U.S. general population (CDC 2022; Olsen et al. 2017). For example, PFBS was detected in less than 5% of serum samples in all National Health and Nutrition Examination Survey (NHANES) years except 2005–'06 (CDC 2022). Both NHANES and the blood donor studies show generally higher levels of long-chain PFAAs in males than females, with generally decreasing serum levels of long-chain PFAAs over time. NHANES 2013–'14 evaluated PFAS in children 3–11 years old (CDC 2022) and found serum levels of PFOS, PFOA, PFHxS, and PFNA generally similar to those in older adolescents and adults in the same time period. It was noted that most of the children studied were born after PFOS manufacturing was phased out in the United States in 2002 (Ye et al. 2018). Long-chain PFAA human serum levels in other industrialized countries are generally similar to the United States (Kato 2015) and may be lower in less developed nations (for example, Afghanistan) where they are less likely to be used industrially and consumer products containing them are less frequently used (Hemat et al. 2010). Testing in 2017 by the North Carolina Department of Health and Human Services (NC DHHS) did not detect HFPO-DA ("GenX") in the blood serum or urine of North Carolina residents with previous or current exposure from private wells, but did detect other PFAS (NC DHHS 2018). A North Carolina State University study of a public water system and its users included a larger list of PFAS analytes and, although no GenX was detected, they identified four newly identified PFAS in the drinking water and blood serum of most participants (Hogue 2019; Hopkins et al. 2018). A study of a potentially exposed population detected ADONA in only a few subjects (Fromme et al. 2017).

Human exposures can result from consumption of fish from waters contaminated with bioaccumulative PFAAs (for example, MDCH 2014). PFSAs with more than eight fluorinated carbons (that is, PFOS and longer chain for PFSAs; PFNA and longer chain for PFCAs) are substantially more bioaccumulative than shorter chain PFAAs, with PFSAs generally more bioaccumulative than PFCAs with the same number of fluorinated carbons (Conder et al. 2008; Martin et al. 2003). When drinking water is contaminated with even relatively low levels of long-chain PFAAs, exposure from drinking water may dominate contributions from exposure sources such as food and consumer products that are prevalent in the general population. For example, USEPA (2011) predicted that ongoing exposure to 20 ng/L PFOA in drinking water will increase serum PFOA levels more than two-fold from the U.S. median of 2 ng/L. Elevated serum levels of long-chain PFAAs have been observed in communities with contaminated drinking water in several U.S. states, including Ohio and West Virginia (WV University 2008; Emmett et al. 2006; Steenland et al. 2009) (Hoffman et al. 2011), New Hampshire (NH DHHS 2015), Alabama (ATSDR 2013), Minnesota (MDH 2009; Landsteiner et al. 2014), New York (NYS DOH 2016), and in other nations, including Germany (Hölzer et al. 2008) and Sweden (Li et al. 2018) (Table 17-6). ATSDR (2022) has conducted exposure assessments that included biomonitoring in eight U.S. locations impacted by PFAS in drinking water.

Understanding exposures to PFAS at different developmental phases (for example, fetus, infant) is important to ensure protection of the most sensitive subpopulations. Evidence for developmental effects from early life exposures to long-chain PFAAs in humans is discussed in Section 17.2.4 and in animals in Section 17.2.5. PFAAs (primarily PFHpA and longer chain PFCAs; PFHxS and longer chain PFSAs) have been detected in human amniotic fluid (Stein et al. 2012; Zhang et al. 2013), umbilical cord blood (Kato 2015; Kudo 2015), and breast milk (Liu et al. 2010; White et al. 2011; Post, Cohn, and Cooper 2012; Kato 2015; Kudo 2015). Although the specific compounds analyzed for and/or detected vary among studies, other PFAAs that have been analyzed for in breast milk rarely exceeded the limit of quantitation (Tao et al. 2008; Tao et al. 2008). Serum levels of several long-chain PFAAs were higher in breast-fed infants than in their mothers and declined slowly following weaning (Fromme et al. 2010), and serum levels of infants who drank formula prepared with PFAS-contaminated water are predicted to be higher than in older individuals using the same water source (Goeden, Greene, and Jacobus 2019). Infants and toddlers may also receive higher exposures because of age-specific behaviors such as hand-to-mouth activity that results in greater ingestion of house dust, and more time spent on floors with treated carpets relative to older children or adults (Trudel et al. 2008; Shoeib et al. 2011).

Elevated serum levels of PFAAs, in some cases >100,000 ng/ml, have been found in industrially exposed workers (Olsen 2015). Serum concentrations of PFCAs (PFHpA and longer) were also increased in professional ski waxing technicians due to exposures to fluorinated ski waxes (Freberg et al. 2010; Nilsson et al. 2010). Higher serum levels of PFDA (Dobraca et al. 2015), PFOS, and PFHxS (Rotander et al. 2015) have been reported in firefighters relative to those in the general population.

17.2.3 Toxicokinetics

PFAAs for which data are available (PFOA, PFHpA, PFHxA, PFOS) were well absorbed orally (≥90%) in rodents (Kudo 2015). PFOA and PFNA were absorbed via inhalation as dusts or aerosols (Kinney, Chromey, and Kennedy 1989; Hinderliter, DeLorme, and Kennedy 2006). PFOA was absorbed to a limited extent from dermal exposure in studies of isolated human and rodent skin (Fasano et al. 2005; Franko et al. 2012). Several recent in vivo studies demonstrate dermal absorption in laboratory animals and humans. Chen et al. (2022) reported that the tested PFAS (PFCAs with 4 to 12 carbons; PFBS, PFHxS, PFOS; 6:2- and 8:2 diPAP) were absorbed after a single application to skin; the extent of dermal absorption varied with compound and dose. Weatherly et al. (2023) reported toxicity and gene expression changes in liver and skin, as well as detection in urine and serum, after daily application of PFPeA, PFHxA, and PFHpA to the skin of mice for 28 days. Abraham and Monien (2022) demonstrated dermal absorption of isotopically labelled PFOA mixed with sunscreen in a human volunteer.

PFAAs, particularly long-chain PFCAs and PFSAs, have unique toxicokinetic properties as compared to other types of POPs. Unlike most other bioaccumulative organic compounds (for example, dioxins, PCBs), PFAAs do not have a high affinity for adipose tissue. In contrast, PFAAs are water soluble, have an affinity for proteins (which varies among compounds), and generally distribute primarily to the liver, blood serum (where they are bound to albumin and other proteins), and kidney (Bischel et al. 2011; Lau 2012, 2015; Kato 2015).

PFAAs are highly resistant to chemical reactions. As such, they are not metabolized, and this is also true for HFPO-DA (Gannon et al. 2016) and ADONA (Gordon 2011). However, PFAA precursors can be metabolized to PFAAs within the body, and reactive intermediates may be formed in these metabolic pathways (Rand and Mabury 2016). Some examples are the metabolism of 6:2 fluorotelomer alcohol (6:2 FTOH) to PFBA, PFPeA, PFHxA, and PFHpA (Buck 2015); 8:2 FTOH to PFOA and PFNA (Kudo 2015; Kabadi et al. 2018); and perfluorooctane sulfonamidoethanols (FOSEs), perfluorooctane sulfonamides (FOSAs), and perfluorooctane sulfonamidoacetic acids (FOSAAs) to PFOS (Gebbink, Berger, and Cousins 2015). Additionally, larger PFAS molecules such as polyfluoroalkyl phosphoric acid diesters (diPAPs) have been found in human blood serum and can be metabolized to FTOHs, which are further metabolized to PFCAs (D’Eon and Mabury 2011; Lee and Mabury 2011).

Table 17-6. Long-chain PFAA serum levels in populations exposed through drinking water (ng/ml = µg/L = ppb)

(Means, medians, and maximums available from the cited studies are shown. AM–arithmetic mean; GM–geometric mean; 95th–95th percentile; — indicates that data are not available)

Location	**Study Population**	**Attributed Source**	**Year**	**PFOA**			**PFOS**			**PFHxS**		
				Mean	***Median***	***Max.***	***Mean***	***Median***	***Max.***	***Mean***	***Median***	***Max.***
C8 Study Population: WV/Ohio (WV University 2008) Includes occupationally exposed subject	n = ~69,000 <1 – >90 yrs. M-48%, F-52%	Industrial–PFOA	2005–06	83 (AM)	28	22,412	23 (AM)	20	759	—	—	—

Location	**Study Population**	**Attributed Source**	**Year**	**PFOA**			**PFOS**			**PFHxS**		
				Mean	***Median***	***Max.***	***Mean***	***Median***	***Max.***	***Mean***	***Median***	***Max.***
Arnsberg, Germany (Hölzer et al. 2008)	n=90 Children 5-6 yrs.	Industrial waste applied to agricultural land–mainly PFOA	2006	25 (AM)	—	97	5 (AM)	—	21	1 (AM)	—	13
	n=164 Mothers 23–49 yrs.			27 (AM)	—	100	6 (AM)	—	17	1 (AM)	—	6
	n=101 Men 18–69 yrs.			29 (AM)	—	78	12 (AM)	—	36	3 (AM)	—	9
East Metro, MN (MDH 2009)	n = 196 20–86 yrs. M-45%, F-55%	Industrial–multiple PFAS	2008–09	23 (AM)	16	177	48 (AM)	41	448	15 (AM)	9	316
Decatur, AL (ATSDR 2013)	n=153 “child” – >60 yrs. M-41%, F-59%	Industrial–multiple PFAS	2010	16 (GM)	—	144	40 (GM)	—	472	6 (GM)	—	59
Ronneby, Sweden (Li et al. 2018)	n = 3418 4–83 yrs. M-47%, F-53%	AFFF	2014	14 (AM)	10	92	245 (AM)	176	1,870	228 (AM)	152	1790
Portsmouth, NH (NH DHHS 2015)	n = 108 < 12 yrs.	AFFF	2015	4 (GM)	5	12	9 (GM)	9	31	6 (GM)	7	26
	n= 363 >12 yrs.			3 (GM)	—	16	8 (GM)	—	75	8 (GM)	—	75
Hoosick Falls, NY (NYS DOH 2016)	n = 2,081 <17 – >60 yrs. M-45%, F-55%	Industrial–PFOA	Feb.–April 2016	24 (GM)	28	—	—	—	—	—	—	—
Merrimack, NH (NH DHHS 2017)	Public water system n = 217	Industrial–PFOA	2016	3.9 (AM)	—	10.1 (95th)	5.5 (AM)	—	15.2 (95th)	1.3 (AM)	—	3.2 (95th)
	Private wells N=219			4.4 (AM)	—	26.6 (95th)	5.4 (AM)	—	16.4 (95th)	1.3 (AM)	—	3.4 (95th)

Excretion of PFAAs and HFPO-DA is primarily through the urine, with a much smaller percentage, if any, eliminated in the feces. In women of childbearing age, excretion also occurs through menstruation and lactation (Harada and Koizumi 2009; Thomsen et al. 2010). Serum PFAS levels were lower in adult males undergoing venesection (ongoing blood withdrawal) for medical reasons (Lorber et al. 2015) and in firefighters who had donated blood, as compared to other firefighters (Rotander et al. 2015). The excretion rate for long-chain PFAAs varies substantially between animal species, and it is much slower in humans than in laboratory animals. Additionally, for some PFAS, including PFOA, PFNA, and others, the excretion rate is very different in males and females of the same rodent species, likely due to differences in the extent of secretion and reabsorption by organic anion transporter proteins (OATs) and possibly other transporter proteins in the kidney, reviewed in Lau (2012); Lau (2015); Kudo (2015); and USEPA (2023). Half-lives in rodents, nonhuman primates, and humans for the PFAS included in this section are shown in Table 17-7.

Table 17-7. Half-lives of PFCAs, PFSAs, and perfluoroethers in rodents, nonhuman primates, and humans

Notes: No information was located for PFPeA, PFDoA, PFTrDA, PFTeDA, PFPeS, PFNS, PFDS, ADONA; — indicates that data are not available; h–hour, d–day, y–year.

	Mouse		Rat		Nonhuman primate		Human	
	Male	Female	Male	Female	Male	Female	Male	Female
PFCAs								
PFBA	13 h[a]	2.9 h[a]	9.2 h[a]	1.8 h[a]	40 h[a]	41 h[a]	72 h[a] (O; mean)	87 h[a] (O; mean)
PFHxA	~1 h[b]		~2 h[c]	~2 h[c]	5.3 h[c]	2.4 h[c]	32 d[e] (O; GM)	—
					14–47 h[d]			
PFHpA	—-	—-	2.4 h[f]	1.2 h[f]	—-	—-	—	<50 yrs. of age-1.2 y[g] (G-U)
							All M & F >50 yrs. of age-1.5 y[g] (G-U)	
PFOA	19 d[h]	17 d[h]	4–6 d[i]	2-4 h[i]	21 d[j]	30 d[j]	3.8 y (O; mean); 2.4 y (O; GM)[k] 2.3 y[z] (DW; median) 3.3 y[m] (DW; GM) 3.4 y[n] (DW; mean) 2.69 y[n] (DW; mean)	
							15–50 yrs. of age-4.6 y[n] (DW)	15–50 yrs. of age-3.1 y[n] (DW)
PFNA	34–68 d[o,p]	26–69 d[o,p]	30 d[o,p]	1–2 d[o,p]	—-	—-		<50 yrs. of age-2.5 y[g] (G-U)
							All M & F >50 yrs. of age-4.3 y[g] (G-U)	
PFDA	—-	—-	24 d[q]	29 d[q]	—-	—-		<50 yrs. of age-4.5 y[g] (G-U)
							All M & F >50 yrs. of age-12 y[g] (G-U)	
PFUnA	—-	—-	—-	—-	—-	—-		<50 yrs. of age-4.5 y[g] (G-U)
							All M & F >50 yrs. of age-12 y[g] (G-U)	
PFSAs								
PFBS	—-	—-	3.1–4.5 h[r,s]	2.4–4.0 h[r,s]	15–95 h[r,s]	8.1–83 h[r,s]	26 d (O; GM)[s]	
PFPeS	—-	—-	—-	—-	—-	—-	1.03 y[z](DW; median)	
PFHxS	29 d[t]	26 d[t]	29 d[t]	1.8 hd[t]	141 d[t]	87 d[t]	8.5 y (O; mean); 7.3 y (O, GM)[k] 5.3 y[n] (DW)	
							15–50 yrs. of age-7.4 y[n] (DW)	15–50 yrs. of age-4.7 y[n] (DW)
PFHpS	—-	—-	—-	—-	—-	—-	5.0 y[z](DW; median)	

	Mouse		**Rat**		**Nonhuman primate**		**Human**	
	Male	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**
PFOS	40 d[u]	34 d[u]	47–67 d[u,v]	40–48 d[u,v]	132 d[u]	110 d[u]	5.4 y (O; mean); 4.8 y (O; GM)[k] 3.4 y [n] (DW; mean) 2.89 y [n] (linear; DW; mean)	
							15–50 yrs. of age-4.6 y[n] (DW; mean)	15–50 yrs. of age-3.1 y[n] (DW; mean)
Perfluoroether (Replacement for PFOA in fluoropolymer manufacturing processes)								
GenX	21 h[w]	18 h[w]	3 h[x]	<3 h[x]	~2 h[y]	~2 h[y]	—-	—-
PFOS-branched isomers	—-	—-	—-	—-	—-	—-	2.87–5.57 y[z](DW, GM)	

<table>
<tr><th rowspan="2"></th><th colspan="2">Mouse</th><th colspan="2">Rat</th><th colspan="2">Nonhuman primate</th><th colspan="2">Human</th></tr>
<tr><th>Male</th><th>Female</th><th>Male</th><th>Female</th><th>Male</th><th>Female</th><th>Male</th><th>Female</th></tr>
<tr><td colspan="9">DW–Based on decline in serum levels after exposure to contaminated drinking water ended.
GM–Geometric mean.
G-U–Mean value; based on urinary excretion in general population, with modeled menstrual excretion for F < 50 yrs. old. More uncertain than estimates based on decline in serum levels. (Not shown for PFAS with half-lives based on serum decline).
O–based on decline in serum levels in workers or retired workers after exposure ended.
[a] Chang et al. (2008)
[b] Iwai (2011), reported in Russell, Nilsson, and Buck (2013)
[c] Chengelis et al. (2009)
[d] Noker (2001), reported in Russell, Nilsson, and Buck (2013)
[e] Russell, Nilsson, and Buck (2013)
[f] Ohmori et al. (2003)
[g] Zhang et al. (2013)
[h] Johnson and Ober (1979); Kemper and Jepson (2003)
[i] Lau et al. (2006)
[j] Butenhoff et al. (2004)
[k] Olsen et al. (2007)
[l] Bartell et al. (2010)
[m] Brede et al. (2010)
[n] Li et al. (2018)
[o] Tatum-Gibbs et al. (2011)
[p] Ohmori et al. (2003)
[q] Gibbs et al. (2012)
[r] Chengelis et al. (2009)
[s] Olsen et al. (2009)
[t] Sundstrom et al. (2012)
[u] Chang et al. (2012)
[v] Butenhoff (2007)
[w] DuPont (2011)
[x] DuPont (2011)
[y] DuPont (2008)</td></tr>
</table>

As shown in Table 17-7, excretion rates in mammalian species vary among PFAS for which half-life data are available, with short-chain PFAAs and GenX generally excreted more rapidly than longer chain PFAAs. Half-lives in rodents and nonhuman primates are generally in the range of several weeks to several months for long-chain PFAAs, and about 1 hour to several days for short-chain PFAAs and GenX. However, PFOA, PFNA, and PFHxS (reviewed in Kudo 2015) are excreted much more rapidly (hours to days) in female than male rats; this sex difference in rats also exists but is not as pronounced for PFBA, PFHxA, PFHpA, and PFBS (Kudo 2015). This difference in excretion rate is important in interpretation of rat toxicology studies of these compounds, particularly for developmental effects.

Human half-lives for PFAS are longer than in other mammalian species that have been studied, with estimates of several years for long-chain PFAAs (PFOA, PFNA, PFOS, PFHxS); 1 year for PFHpA, and several days to 1 month for shorter chain PFAAs (PFBA, PFHxA, PFBS; Table 17-7). The estimates of human half-life shown in Table 17-7 are based on measured declines in serum PFAS levels in the same individuals over time after a source of elevated exposure, such as occupational exposure or ingestion of contaminated drinking water, ceases. Such estimates are less uncertain than population-based estimates from modeling of PFAS intake and biomonitoring data for serum PFAS levels from different sets of individuals from the general population at different time points. Half-life estimates based on urinary excretion are available for several PFAAs, including some with no serum-based half-life estimates ((Zhang et al. 2013) shown as G-U in Table 17-7); these urinary estimates are less certain because they include modeled estimates of menstrual excretion in women of childbearing age and do not consider fecal excretion or blood loss other than menstruation (for example, blood donation). It should be noted that there are large inter-individual variations in human half-lives, which may arise from physiological factors (for example, differences in renal transport by OATs; Yang, Glover, and Han 2010).

Because of the large species and sex differences in excretion rates, the internal dose resulting from a given administered dose varies widely among species and, in some cases, males and females of the same species. Therefore, interspecies (for example, animal-to-human) comparisons must account for the large interspecies half-life differences with approaches such as use of internal dose (as indicated by serum level) as the dose metric, interspecies toxicokinetic extrapolation based on the ratio of half-lives in humans and animals, or use of physiologically based pharmacokinetic models.

17.2.3.1 Toxicokinetics Relevant to Developmental Exposures

Toxicokinetics relevant to developmental exposures to PFAAs are important because developmental effects are sensitive endpoints for toxicity of long-chain PFAAs in rodents, and prenatal exposure to some long-chain PFAA was associated with decreased fetal growth in some human epidemiology studies (see Section 17.2.3.4). Developmental exposures have been studied in rodents for several PFAAs, but not in nonhuman primates. PFAAs cross the placenta to reach the developing fetus in both humans and rodents (reviewed in Lau 2012 and Kudo 2015), and are transferred to milk, resulting in exposure via lactation (Luebker et al. 2005; White et al. 2009; Kato 2015). In humans, long-chain PFAAs have been detected in cord blood (for example, Wang et al. 2019) and amniotic fluid (Stein et al. 2012; Zhang et al. 2013).

In humans, the greatest exposures to PFAAs in breast milk occur during the first few months of infancy because both PFAA concentrations in milk and the breast milk ingestion rate on a BW basis (ml/kg/day) are highest then; PFAA levels in milk may be lower in mothers who previously nursed other infants (Tao et al. 2008; Haug et al. 2011; Thomsen et al. 2010). Serum concentrations of long-chain PFAAs in breast-fed infants increase several-fold from the levels at birth during the first few months of life, followed by a decline in older infancy and early childhood (Fromme et al. 2010; Mogensen et al. 2015; Verner et al. 2016, 2016; MDH 2018, 2019; reviewed in NJDWQI 2015, 2017, 2018). Because of their higher rate of fluid consumption on a BW basis (USEPA 2019), exposures to infants who consume formula prepared with PFAS-contaminated water are also highest during the first few months of life. Goeden, Greene, and Jacobus (2019) presented a model that predicts transplacental transfer and exposure to breast-fed and formula-fed infants for long-chain PFAAs in drinking water.

17.2.3.2 Relationship of Human Exposures to Serum Levels

Clearance factors (CL) that describe the relationship between oral exposures or dose (ng/kg/day) and steady-state serum levels (ng/L) in humans have been developed for PFOA (Lorber and Egeghy 2011; USEPA 2016) and PFOS (USEPA 2016):

$$\text{Dose [ng/kg/day]} \times \text{CL [L/kg/day]} = \text{serum concentration [ng/L].}$$

These clearance factors, which indicate bioaccumulative potential, are based on average values for human PFAS half-lives and volumes of distribution (Vd);

$$\text{CL [L/kg/day]} = \text{Vd [L/kg Body Wt]} \times \text{[Ln2/half-life in days].}$$

Where Ln2 is the natural log of 2.

When combined with mean daily U.S. water ingestion rates (USEPA 2011), the CLs have been used to predict the expected average increase in serum levels (above the “baseline” serum level from non-drinking water sources) that results from ongoing exposure to a given drinking water concentration of PFOA or PFOS (Bartell 2017; NJDWQI 2017; Post, Gleason, and Cooper 2017). For PFOA, this average serum:drinking water ratio was predicted to be greater than 100:1 (NJDWQI 2017); this ratio is consistent with data from exposed populations and toxicokinetic modeling (Emmett et al. 2006; Hoffman et al. 2011; Bartell 2017). The CL for PFOS predicts an average serum:drinking water ratio of about 200:1 (NJDWQI 2018; Post, Gleason, and Cooper 2017; Lu and Bartell 2020), and available toxicokinetic data also support an estimated ratio of 200:1 for PFNA (NJDWQI 2015; Lu and Bartell 2020) and PFHxS (Lu and Bartell 2020). It should be noted that PFAA serum:drinking water ratios vary among individuals using the same source of contaminated drinking water, due to inter-individual differences in daily water consumption rates (L/kg/day) and/or physiological differences relevant to toxicokinetics.

Bartell (2017), Lu and Bartell (2020), and ATSDR (2022) have developed online calculators that provide estimates of an individual's serum concentrations of PFOA, PFOS, PFNA, and PFHxS from the information that is entered, including drinking water levels of these PFAS and other relevant factors. These estimates are based on long-term exposure to a constant drinking water concentration and that serum PFAS concentrations are impacted by interindividual variability in both toxicokinetic factors (for example, PFAS half-lives) and daily drinking water ingestion rate.

17.2.3.3 Isomer-Specific Toxicokinetics

Some PFAAs exist as a mixture of linear and branched isomers; the isomer profile varies depending on the manufacturing process used (telomerization yields primarily linear PFAS; electrochemical fluorination yields a mixture of linear and branched PFAS; Section 2.2.5.2. Toxicokinetics may differ among isomers of the same PFAA in rodents (Loveless et al. 2006; De Silva et al. 2009) and humans (Zhang et al. 2013; Gao et al. 2015; Beesoon et al. 2011; Xu et al. 2020; Li et al. 2022).

17.2.4 Human Epidemiology Studies

As discussed in Section 7.1.3, the epidemiological database for long-chain PFAAs, particularly PFOA and PFOS, is more extensive than for many other environmental contaminants. Many of the studies are recent, and the number of available studies is constantly increasing. In contrast, there are few or no epidemiology studies for many other PFAS (Carlson et al. 2022; Radke et al. 2022).

Many U.S. general population studies are based on data from NHANES (CDC 2022), and other general population studies come from various worldwide locations. These include studies of specific subpopulations such as pregnant women, infants, children, or the elderly, as well as evaluations of associations of prenatal exposures with effects later in life. Data on communities exposed to PFOA through contaminated drinking water come primarily from the C8 Health Study evaluations of approximately 70,000 Ohio and West Virginia residents exposed in drinking water for at least 1 year at concentrations of 50 ng/L to >3,000 ng/L, including evaluations by the C8 Science Panel (Frisbee et al. 2009; C8 Science Panel 2020). This panel consisted of three prominent environmental epidemiologists charged with determining whether there are "probable links" (defined as "given the scientific evidence available, it is more likely than not that a connection exists between C8 exposure and a particular human disease among class members") between PFOA exposures in this study group and disease. Researchers who participated in the C8 Science Panel recently evaluated current epidemiologic evidence for PFOA and the diseases for which the C8 Science Panel had concluded in 2011–12 that there was a "probable link" with PFOA exposure (kidney and testicular cancer, high cholesterol, thyroid disease, pregnancy-induced hypertension, ulcerative colitis; C8 Science Panel Probable Link reports (C8 Science Panel 2017). They also reviewed evidence for associations of PFOA and additional health effects (Steenland et al. 2020). The conclusions of Steenland et al. (2020) for specific health effects are discussed below.

Until recently, health effects studies were not available from communities with drinking water contaminated with either the other PFAS discussed in this section or the complex mixtures of PFAS present in AFFF. Studies of associations of PFAS with a variety of health effects in a community exposed to AFFF-contaminated drinking water in Sweden have now been reported (Andersson et al. 2019; Li et al. 2020, 2021, 2022; Xu et al. 2020, 2022; Hammarstrand et al. 2021; Nielsen and Joud 2021; Engstrom et al. 2022; Nielsen et al. 2022). Additional epidemiological studies of seven communities exposed to PFAS found in AFFF or specific PFAS other than PFOA (for example, PFNA) are now being conducted through the ATSDR-funded multisite study (ATSDR 2022).

Finally, health effects of several long-chain PFAAs, including PFOA, PFOS, and PFNA, have been studied in occupationally exposed workers (Khalil 2015). Because these workers were primarily male, relatively few women were included in these studies.

Exposure assessment in most but not all of the epidemiology studies of PFAS is based on blood serum levels of PFAS as an indicator of internal dose. The studies often evaluate associations between health endpoints and multiple PFAS detected in blood. Serum levels of long-chain PFAAs are indicators of long-term exposures (Section 7.1.2) that reflect individual differences in both exposure (for example, daily water consumption) and rate of excretion. Therefore, serum levels are less uncertain as indicators of exposure than external parameters such as drinking water concentration. In contrast to long-chain PFAS, there is little epidemiological information on short-chain PFAS because they are infrequently detected in blood serum due to their more rapid excretion. Exposure assessment in some of the C8 studies of communities with PFOA exposure from an industrial source is based on serum PFOA levels estimated from modeling of drinking water and air PFOA concentrations over time, rather than measured serum levels Savitz et al. 2012; Winquist and Steenland 2014, 2014; Dhingra et al. 2016, 2016; Herrick et al. 2017). Finally, exposure is based on job classification, rather than serum PFAA measurements in some occupational studies of PFOA (Gilliland and Mandel 1993; Leonard 2003; Lundin et al. 2009; Raleigh et al. 2014), PFNA (Mundt et al. 2007), and PFOS (Alexander et al. 2003; Olsen et al. 2004; Alexander and Olsen 2007; Grice et al. 2007).

As is the case for epidemiologic studies of environmental contaminants in general, the human studies of PFAAs are observational, in contrast to toxicology studies, which are experimental. Additionally, most epidemiology studies of PFAAs are cross-sectional, although some use other designs (prospective, retrospective, case-control). In cross-sectional studies, exposure and outcome are evaluated at the same point in time. Such cross-sectional studies cannot reveal whether increased exposure led to the health endpoint or vice versa, and reverse causality (for example, when a physiological change affects serum PFAS levels, rather than the serum PFAS levels causing the physiological change) has been hypothesized by some researchers as partially or totally explaining some of the associations in the epidemiological literature, including reduced birth weight and decreased kidney function (reviewed in NJDWQI 2017). In general, publications of epidemiology studies report results in terms of associations with the endpoints of interest based on statistical analysis. When there are multiple studies of associations of an environmental contaminant such as PFAA(s) with a health endpoint, results often differ among studies. The differing results can arise from difference in the study design (for example, sex, age, ethnicity of population studied; magnitude and/or duration of exposure; method for assessment of endpoint of interest), size of population studied (may be too small to detect statistically significant associations), method used for statistical analysis, consideration of potential confounding factors, or chance.

Therefore, conclusions about whether the overall body of evidence supports an association are based on scientific judgment and may differ among scientists who review the same body of data. Additionally, for PFAS, because many new epidemiology studies continually become available, more recent evaluations may include considerable data not available for earlier evaluations. Because observational studies are not designed to prove causality for health effects, conclusions about evidence for causality are based on criteria, such as the Hill criteria (Lucas and McMichael 2005) related to the overall body of relevant scientific information (for example, consistency, dose-response, biological plausibility, potential for reverse causality). For example, observations of associations with the same health endpoint in studies from multiple locations and in different types of populations (for example, general population, exposed communities, workers), as is the case for some effects associated with PFOA and PFOS (Post, Cohn, and Cooper 2012; USEPA 2023; USEPA 2023) strengthen the weight of evidence for that effect. Use of systematic review methods are increasingly used to evaluate the quality of epidemiological studies as well as the potential confounders (for example, USEPA 2023). As is the case for associations, conclusions about causality may differ among scientists reviewing the same body of data.

17.2.4.1 Noncancer Health Endpoints

This section summarizes information for various categories of noncancer health endpoints: Changes in systemic markers, Fetal growth, Immune system effects, Thyroid effects, and Other effects.

Systemic Markers

For PFOA and PFOS (Khalil 2015; USEPA 2023, 2016; NJDWQI 2017, 2018; ATSDR 2021), PFNA (NJDWQI 2015; ATSDR 2021), and PFDeA (ATSDR 2021), the cited reviews concluded that associations are generally consistent for increases in total cholesterol and/or low-density lipoproteins. Australia Government DOH (2018) concluded, based on a review of key reports and published systematic reviews, that an association of both PFOA and PFOS with small changes in cholesterol is generally observed. Additionally, the C8 Science Panel concluded that there is a “probable link” between PFOA and clinically defined high cholesterol (C8 Science Panel 2012). Rappazzo, Coffman, and Hines (2017) concluded that the evidence for an association of prenatal or childhood exposure to PFAS with increased cholesterol is generally consistent; studies reviewed found associations with PFOA, PFOS, PFNA, and/or total PFAS. Regarding causality, NJDWQI (2017) concluded that the evidence supports multiple criteria for a causal relationship between increased serum cholesterol and PFOA, while Australia Government DOH (2018) concluded that it cannot be established whether PFOA or PFOS causes increased cholesterol based on currently available data. NASEM (2022) concluded that there is sufficient evidence for an association of PFAS with dyslipidemia in adults and children.

Steenland et al. (2020) noted continued consistent findings of an association between PFOA and high cholesterol. However, although high cholesterol is a risk factor for cardiovascular disease, the C8 Science Panel did not find a “probable link” for PFOA and heart disease, and subsequent studies have also not found an association. Relevant to this issue, Steenland et al. (2020) stated that this apparent inconsistency might be explained by associations of PFOA not only with increased cholesterol, but with increased high density lipoprotein (HDL) and decreased C-reactive protein, both of which decrease heart disease risk

Most reviews have concluded that PFOA (Gleason et al. 2015; Khalil 2015; 2023; NJDWQI; ATSDR 2021) and PFNA (NJDWQI 2015) are generally associated with increases in certain liver enzymes, particularly alanine aminotransferase (ALT). NJDWQI (2017) concluded that there is some evidence to support a causal relationship between PFOA and ALT. In contrast, most earlier evaluations of PFOS have found weaker or no evidence for associations with increased liver enzymes (Gleason et al. 2015; Khalil 2015; NJDWQI 2018, 2018. However, ATSDR (2021), p. 26, concluded that "increases in serum enzymes and decreases in serum bilirubin, observed in studies of PFOA, PFOS, and PFHxS, are suggestive of liver alterations." NASEM (2022) concluded that there is limited or suggestive evidence for an association of PFAS with liver enzyme alterations in adults and children. For PFOA, USEPA (2023) concluded that there is consistent evidence of a positive association with ALT in adults, at median PFOA levels as low as 1.3 ng/mL. USEPA (2023), p. 3-28 to 3-29, concluded that "there is generally consistent evidence of a positive association between exposure to PFOS and ALT. However, one source of uncertainty in epidemiology studies of PFAS is confounding across the PFAS, as individuals are exposed to a mixture of PFAS and it is difficult to disentangle the effects. This cannot be ruled out in this body of evidence given the attenuation of the association in Lin et al. (2010), the only general population study that performed multi-pollutant modeling. … Thus, while there is evidence of an association between PFOS and ALT, there is residual uncertainty. "Australia Government DOH (2018) concluded that an association of PFOA and PFOS with elevated levels of the liver enzyme ALT was observed in many studies. Steenland et al. (2020) also concluded that the limited currently available data do not support an association of PFOA and liver disease. However, Steenland et al. (2020) noted that the lack of human studies with sufficient power to detect this effect, well established liver toxicity of PFOA in experimental animals, bioaccumulation of PFOA in human liver, and extensive evidence for associations with markers of liver damage indicate the need for additional research, particularly in regard to potential associations with nonalcoholic fatty liver disease.

Various reviews have concluded that there is some evidence or limited evidence for an association of increased serum uric acid and/or hyperuricemia with exposure to PFOA, PFOS, and/or PFNA (Gleason et al. 2015; Khalil 2015; NJDWQI 2015, 2017, 2018; Australia Government DOH 2018).

Fetal Growth

Exposure to PFOA and PFOS were associated with relatively small changes in measures of decreased fetal growth (for example, birth weight, [glossary_exclude]head [/glossary_exclude]circumference) in most studies, while some studies did not find such an association. A systematic review and meta-analysis by Johnson et al. (2014) found that there is "sufficient" human evidence that developmental exposure to PFOA reduces fetal growth in humans and provided a quantitative estimate of the decrease in birth weight per ng/ml serum PFOA. The main analysis included nine studies in which maternal or umbilical cord serum PFOA levels were measured in pregnant women. These studies met other inclusion criteria defined by the researchers; study subjects were from the general population in various locations. An additional analysis included a large study from the C8 Health Study population with exposure from contaminated drinking water in which maternal serum levels were retrospectively modeled. PFOA was associated with decreased birth weight in most of the studies from the general population but not in the study of the more highly exposed community. Inclusion of this study from the C8 Health Study population, in which serum PFOA levels during pregnancy were modeled from pre-pregnancy serum PFOA data and thus would not be impacted by potential changes in GFR, reduced the magnitude of decreased birth weight per ng/ml serum PFOA.

Several other reviews also evaluated the associations of PFOA and PFOS with decreased fetal growth. Bach et al. (2015) concluded that PFOA and PFOS are associated with decreased birth weight in most studies, but that associations in some studies were not statistically significant, and that the existing information is insufficient to determine whether or not there is an association. Khalil (2015) concluded that there is inconsistent evidence for association of decreased birth weight and PFAS. A later meta-analysis by Negri et al. (2017), which included more recent studies not considered by Johnson et al. (2014), also reported a quantitative relationship between decreased birth weight and serum PFOA and PFOS levels. A recent meta-analysis by Steenland, Barry, and Savitz (2018) considered additional studies not included in the two earlier meta-analyses, including the large studies from the C8 Health Study in which serum PFOA levels during pregnancy were modeled from pre-pregnancy serum PFOA data. Although Johnson et al. (2014) concluded that results from studies without measured serum data during pregnancy are too uncertain to include in a metanalysis, Steenland, Barry, and Savitz (2018) concluded that use of modeled or pre-pregnancy serum data may actually be preferable to serum levels measured during pregnancy because these exposure estimates would not be affected by potential reverse causality or confounding related to expansion of maternal plasma volume during pregnancy or renal glomerular filtration rate. Additionally, Steenland, Barry, and Savitz (2018) concluded that the decrease in birth weight in studies based on late pregnancy serum PFOA levels was larger than in those based on preconception or early pregnancy serum PFOA levels. They concluded that these findings are consistent with confounding or reverse causality as an explanation for the observed association of PFOA and decreased birth weight. A systematic review and modeling effort by Verner et al. (2015) found that PFOA is associated with decreased birth weight, and that a portion (less than half) of the reduction in birth weight results from confounding by associations of PFAS with decreases in both birth weight and maternal renal glomerular filtration rate (that is, reverse causality). USEPA (2023, 2023) concluded that there is general consistency in associations of PFOA and PFOS with decreased fetal growth, including low birthweight/small for gestational age. However, they noted uncertainties about the potential bias due to impact of changes in maternal hemodynamics, which may impact both serum PFAS levels and fetal growth, in the studies in which serum PFAS levels were evaluated later in pregnancy. The USEPA (2023) also concluded that PFDA is a likely developmental hazard based on evidence of decreased birth weight from studies of exposed humans where PFDA was measured during pregnancy.

ATSDR (2021), p.27, concluded that “evidence is suggestive of an association between serum PFOA and PFOS and small decreases in birth weight; the decrease in birth weight is <20 g (0.7 ounces) per 1 ng/mL increase in blood PFOA or PFOS level.” NASEM (2022) concluded that there is sufficient evidence for an association of PFAS with decreased infant and fetal growth. Australia Government DOH (2018) concluded that PFAS exposure was often associated with generally small decreases in weight and length at birth in general population studies. Steenland et al. (2020) reviewed the factors considered in evaluation of epidemiologic studies of PFAS and birthweight that are discussed above and concluded that collectively, the studies of PFOA and birthweight that are currently available provide inconsistent results.

Immune System Effects

Of the several potential effects of PFAS on immune function, the discussion below focuses on associations with antibody response to vaccines, including in children, because this endpoint has been evaluated and reviewed most extensively. A systematic review by the National Toxicology Program (NTP 2016), p.1, concluded that PFOA and PFOS are “presumed to be an immune hazard to humans” based on a high level of evidence from animal studies and a moderate level of evidence from human studies for suppression of antibody response. ATSDR (2021), p.27, concluded that “evidence is suggestive of an association between serum PFOA, PFOS, PFHxS, and PFDeA (meaning PFDA) levels and decreased antibody responses to vaccines.” For PFOA, PFOS, PFHxS and PFDA, the USEPA (2023) identified decreased antibody response to vaccination in children as an effect of exposure to these PFAS. Rappazzo, Coffman, and Hines (2017) found that there is generally consistent evidence for association of PFAS with this effect in children. NJDWQI (2017, 2018) concluded for PFOA that associations and decreased vaccine response are consistent among studies, and for PFOA, while decreased vaccine response was consistently observed, evidence is limited because most of the vaccine types were evaluated in only one or two studies. Pachkowski, Post, and Stern (2019) concluded that there is evidence that PFOS is associated with a decrease in some vaccine antibody responses following vaccination. Chang et al. (2016) concluded that a consistent association with vaccine response in general has not been demonstrated for PFOA and PFOS, and that some associations for specific vaccines are “striking in magnitude” but require replication in other studies. Australia Government DOH (2018), p. 11, concluded, based on review of key reports and systematic reviews, that “the strongest evidence for a link between PFAS and clinically important immunological effects is for impaired vaccine response.” They note both that the overall human evidence is weak, but that animal data suggests that “PFAS may alter immune function at concentrations found in humans with environmental and occupational exposures.” Khalil (2015) stated that PFAS exposure has been associated with immunotoxicity, including decreased vaccine response, but that the data are inconsistent. NASEM (2022) concluded that there is sufficient evidence for an association of PFAS with decreased antibody response in adults and children. USEPA (2023, 2023) concluded that PFOA and PFOS are associated with decreased antibody response to vaccines in children and concluded that the dose-response for each of these two PFAS can be modeled from the available human studies.

The C8 Science Panel concluded in 2012 that there was not a probable link between PFOA and common infections. Steenland et al. (2020) noted that there was insufficient evidence to infer such a probable link at that time, and that subsequent human and animal studies have evaluated the potential for PFOA to cause immunosuppression (for example, decreased vaccine response, increased infection) and hypersensitivity (for example, asthma, allergy). They reviewed the conclusions of several agencies (NTP 2016; ATSDR 2018 draft; EFSA 2018) and other available reviews regarding the evidence for immune system effects of PFOA, as well as recent studies that are relevant to this topic. The overall conclusion made by Steenland et al. (2020) was that “a relatively large number of studies consistently report that PFOA impairs immune function,” but that “evidence that PFOA increases the risk of infectious disease or asthma is inconsistent.”

Thyroid Effects

Evaluations of PFAAs and thyroid disease have reached varying conclusions. Although stating that the overall database was mixed, the C8 Science Panel determined a "probable link" for PFOA and thyroid disease (C8 Science Panel 2012). (NJDWQI 2017, 2018) found limited evidence for association of PFOA and thyroid disease, while associations of PFOS with thyroid disease were not noted, and Khalil (2015) found that the data for PFAS in general are inconsistent. Australia Government DOH (2018) concluded that "there are no consistent associations between any particular PFAS and thyroid hormones," and that there is limited evidence of an association between PFOA and thyroid disease in women but not in men. Rappazzo, Coffman, and Hines (2017) stated that conclusions about PFAS and thyroid disease in children cannot be reached with certainty due to the small number of studies and variable results. Coperchini et al. (2017) found that hypothyroidism was the most consistent thyroid effect for PFOA, and for PFOS to a lesser extent, with women and children most susceptible. Ballesteros et al. (2017) stated that although there is a small number of studies with comparable data, there is some consistency in evidence for increased thyroid-stimulating hormone (TSH) with PFHxS and PFOS in pregnant women, and with PFNA TSH in teenage boys; associations with thyroid disease were not noted. More recently, a very large study (n = ~ 63,000) evaluated thyroid diseases in a Swedish community in which one-third of the population had previous residential exposure to very high levels of PFOS (8,000 ng/L) and PFHxS (17,000 ng/L) in drinking water. (Andersson et al. 2019). A consistent pattern of increased risk of hypothyroidism or hyperthyroidism was not found in men or women with residential exposure to the contaminated water. Steenland et al. (2020) concluded that there is less evidence for an association of PFOA and thyroid disease than when the "probable link" conclusion for this effect was made, and that studies of PFOA and thyroid hormone levels report inconsistent results. Similarly, ATSDR (2021), p.264, concluded that associations between PFOA, PFOS, PFHxS, PFNA, PFDA, and PFUnA and thyroid-related hormones and thyroid disease are inconsistent across studies, with the majority of studies not finding associations, and that most of the small number of studies of PFDoDA and thyroid hormones did not find "consistent associations." NASEM (2022) concluded that there is limited or suggestive evidence for an association of PFAS with thyroid disease and dysfunction in adults and children. USEPA (2023) did not prioritize PFOA and thyroid disease as one of the key endpoints for evaluation of epidemiological associations. For PFOS, USEPA (2023) concluded that there is "slight evidence to suggest human endocrine toxicity, including associations between PFOS exposure and thyroid disease," and that this conclusion is based on only one study rated as being of high confidence.

Other Effects

The C8 Science Panel also found probable links for PFOA with ulcerative colitis (C8 Science Panel 2012) and pregnancy-induced hypertension [PIH] (C8 Science Panel 2012); PIH was also associated with PFOS in the same two studies that linked it with PFOA (Stein, Savitz, and Dougan 2009; Darrow, Stein, and Steenland 2013). ATSDR (2021), p.26, concluded that "there is suggestive epidemiological evidence for an association between serum PFOA and PFOS and [PIH] and/or pre-eclampsia." In the opinion of Steenland et al. (2020), current evidence continues to support a link of PFOA and ulcerative colitis, although more research is needed for a definitive conclusion, and NASEM (2022) concluded that there is limited or suggestive evidence for association of PFAS and this effect in adults. For pregnancy-induced hypertension, Steenland et al. (2020) reported mixed results; one recent study found an association with preeclampsia, a related effect, while another did not, and NASEM (2022) concluded that there is limited or suggestive evidence for association of PFAS and these effects.

For many other epidemiological endpoints that have been studied, generally consistent associations were not found and/or the available data are too limited to make firm conclusions.

It is notable that associations for several of the effects mentioned above (serum lipids, liver enzymes, vaccine response, birth weight) were observed even within the exposure range prevalent in the general population (without specific exposures from environmental sources), as well as at higher exposures. For several of these effects (for example, cholesterol—Steenland et al. 2009; Frisbee et al. 2010; ALT—Gallo et al. 2012), the dose-response curves (for example, serum lipids, liver enzymes) are steepest at very low exposures with a much flatter slope approaching a plateau at relatively low serum concentrations (for example, ~40 ng/L for PFOA and cholesterol).

17.2.4.2 Carcinogenicity

Several evaluations of the epidemiological evidence for carcinogenicity are available for PFOA and PFOS, while such evaluations have not been conducted for other PFAAs. The C8 Science Panel (2012) found a "probable link" of PFOA with testicular and kidney cancer based on an increased incidence of these cancers in the Ohio and West Virginia communities with drinking water exposure as well as data from other human and animal studies. Although some other occupational studies of PFOA, such as Raleigh et al. (2014), did not find increased incidence of these tumors, increased kidney cancer was reported in workers exposed to PFOA in the West Virginia industrial facility (Steenland and Woskie 2012). In consideration of these findings, IARC (2016) classified PFOA as "possibly carcinogenic to humans" (Group 2B) based on limited evidence that PFOA causes testicular and renal cancer, and limited evidence in experimental animals. Based on reviews of key reports and systematic reviews, the Australia Government DOH (2018), p.70, concluded that “the evidence on cancer risk is limited;” that it is possible that PFOA is associated with an increased risk of kidney and testicular cancer; and that the evidence does not support PFAS being a major contributor to cancer burden in workers or exposed community populations.

A recent study by the National Cancer Institute (Shearer et al. 2021) evaluated associations of serum concentrations of PFOA and other PFAS with renal cell cancer in a subset of participants in a much larger ongoing cancer screening trial. The analysis included 324 subjects diagnosed with renal cell cancer and 324 individually matched controls. PFAS were measured in blood samples taken prior to cancer diagnosis, and serum PFOA concentrations were within the range that was prevalent in the general population at the time of sample collection (1993–2001). Increased serum PFOA was associated with increased risk of renal cell cancer. This association remained even when subjects with decreased kidney function were excluded, and when only subjects with serum PFAS levels measured ≥ 8 years before cancer diagnosis were included. Associations of serum PFOS and PFHxS with increased renal cell cancer risk were not statistically significant after adjustment for the other PFAS, while the association of increased risk with PFOA remained after this adjustment. The authors concluded that these results “add substantially to the weight of evidence that PFOA is a renal carcinogen and may have important public health implications.”

Steenland et al. (2020) concluded that the evidence for an association of PFOA and kidney and testicular cancer remains “supportive but not definitive.” They stated that although the results of three newer studies (published since the C8 Panel’s reports) are not consistent, the evidence for an association of PFOA with kidney cancer is strengthened by positive findings in the recent large case-control study in the general population (Shearer et al 2021).

NJDWQI (2017)–PFOA, NJDWQI (2018)–PFOS, concluded that PFOA and PFOS have suggestive evidence for human carcinogenicity, based primarily on animal data, while a more recent evaluation (NJDWQI 2023) concluded that current evidence for PFOA indicates that it is a likely human carcinogen. USEPA (2023) concluded that PFOA is a likely human carcinogen, citing recent animal (NTP 2020) and human (Shearer et al. 2021) studies that add support to earlier evidence of carcinogenicity. USEPA (2023) also concluded that PFOS is a likely human carcinogen, with a determination of a statistically significant trend for increased pancreatic acinar carcinomas in the chronic rat study (Thomford 2002; Butenhoff et al. 2012) adding support to earlier evidence. USEPA (2018) also concluded that GenX has suggestive evidence for human carcinogenicity. NASEM (2022) concluded that there is sufficient evidence for an association of PFAS and kidney cancer in adults and that there is limited or suggestive evidence for PFAS and breast and testicular cancer in adults.

In contrast to PFOA, studies of cancer incidence in large populations with exposure to contaminated drinking water with elevated levels of only PFOS are not available although a recent study evaluated communities with exposure to drinking water contaminated with PFOA, PFOS, and PFHxS (present at the highest concentration) from AFFF (Li et al. 2022). Arrieta-Cortes et al. (2017) concluded that while associations with cancer were not observed in the available occupational and general population studies of PFOS, such associations cannot be ruled out because problems with the studies may have precluded detection of associations if they were present. They therefore concluded that there is “inadequate evidence of carcinogenicity” based on the human data. Chang et al. (2014) stated that “many positive associations with PFOA exposure were detected in community settings” but were not confirmed in studies of workers with much higher exposures, although increases in certain cancers in some occupational studies are noted within the paper. They concluded that a causal association between PFOA or PFOS and human cancer is not supported by the currently available epidemiological evidence.

17.2.5 Animal Toxicology Studies

Many scientific considerations and decision points are involved in developing human health toxicity factors from animal toxicology data. In the hazard identification component of the toxicity factor development, the toxicological endpoint selected as the basis for the reference dose should be determined to be well established (that is, supported by multiple studies), related to an adverse health outcome, and relevant to humans based on mode of action considerations.

Peroxisome proliferator-activated receptor-α (PPAR-α) is a nuclear receptor found in many human and animal tissues that is involved with numerous physiological processes (Corton, Anderson, and Stauber 2000; Michalik et al. 2006). The role of PPAR-α in the effects caused by PFAS and the human relevance of effects in rodents that are mediated by PPAR-α have been a focus of research on the mode of action for the toxicological effects of PFAAs (Lau 2012; Post, Gleason, and Cooper 2017). As reviewed by Post, Gleason, and Cooper (2017), most PFAAs that have been evaluated for this effect can activate PPAR-α to some extent. Specific toxic effects of some PFAAs in rodent models occur wholly or partially via PPAR-α, while other effects are independent of PPAR-α. One important example is hepatic toxicity of PFAAs. For PFOS, hepatic effects are clearly primarily PPAR-α independent, while hepatic effects of PFOA and PFNA involve substantial contributions from both PPAR-α dependent and independent processes.

In the dose-response evaluation portion of toxicity factor development, the selected endpoint must provide the data needed to determine a point of departure (that is, benchmark dose [BMD], NOAEL, or LOAEL). To appropriately account for the large differences in PFAA half-lives among species, and among sexes of the same species in some cases, dose-response evaluation for long-chain PFAAs is most appropriately based on internal dose, as indicated by serum level, rather than external (administered) dose. Finally, in development of RfDs, uncertainty factors appropriate to the specific study and endpoint are selected and applied to the point of departure to account for factors such as sensitive human subpopulations, interspecies differences, shorter-than-chronic exposure duration, extrapolation from a NOAEL to a LOAEL, and potentially more sensitive toxicological effects (Section 8.3).

Toxicological effects that have been reported as statistically significant in mammalian laboratory animal studies for each PFAS, with relevant citations, are presented in the Table 17-8 Toxicological Effects Excel file. The sections following the table present general discussions of systemic, reproductive and developmental, and carcinogenic effects of these PFAS.

17.2.5.1 Systemic Effects

All of the PFAS included in the Table 17-8 Toxicological Effects Excel file for which data are available caused increased liver weight in the rodent and nonhuman primate species studied. For most of these PFAS, increased liver weight was accompanied by hepatocellular hypertrophy. Developmental (in utero or lactational) exposures to some PFAAs caused increased liver weight in rodent offspring. Many PFCAs, as well as PFOS and GenX, caused additional hepatic effects that are more severe in nature such as hepatocellular necrosis and/or vacuolation in rodents and nonhuman primates, or hepatic lipid accumulation in rodents. For PFOA (Butenhoff et al. 2012; NJDWQI 2017) and PFOS (Butenhoff et al. 2012; NJDWQI 2018), these hepatic effects increased in severity with longer duration of exposure and may represent a progression to neoplastic changes, including hepatic adenomas. Additional effects reported for some PFAS include bile duct toxicity in rodents and increased serum levels of liver enzymes in rodents and/or nonhuman primates.

Some PFAAs and PFECAs caused decreased serum cholesterol in rodents and/or nonhuman primates. The increased cholesterol in humans associated with much lower exposures to some PFAS may be attributable to interspecies differences, such as differences in activity of relevant receptors involved with cholesterol metabolism. However, these contrasting observations in rodents and humans may also arise from differences in the fat content of a typical low-fat laboratory diet and the higher fat diet in the humans who were studied (Tan et al. 2013; Rebholz et al. 2016), or to dose-related differences in this response, because the doses in the toxicology studies are much higher than human exposure levels.

Some long-chain PFAAs caused immune system toxicity in the (Table 17-8 Toxicological Effects Excel file. Decreased antibody response to antigens has been identified as a sensitive endpoint for PFOA and PFOS toxicity, and this endpoint in animal studies have been used as the basis for toxicity factors and health-based regulatory criteria developed by government agencies, including MDH (2019); ATSDR (2021); NJDWQI (2018); Pachkowski, Post, and Stern (2019).

The majority of PFAS covered herein have not been tested for neurobehavioral effects. Of those PFAAs that have been evaluated in rodents, exposure-related effects were not observed for PFBA and PFHxA, while exposure of adult rodents to PFOS and PFDA caused effects including changes in learning, memory, activity, and habituation or other effects indicative of cognitive defects (see studies cited in the Table 17-8 Toxicological Effects Excel file). Additionally, developmental exposures to PFOA, PFOS, and PFHxS caused persistent neurobehavioral effects in mice (Johansson, Eriksson, and Viberg 2009; Onishchenko et al. 2011; Lee and Viberg 2013).

17.2.5.2 Reproductive and Developmental

Reproductive effects in males and females and developmental effects of several PFAS have been evaluated in rodents (Table 17-8 Toxicological Effects Excel file), but these effects have not been studied in nonhuman primates. In addition to the considerations common to developmental toxicity studies in general, the much faster excretion of several PFAS in female rats than in males must be considered when interpreting results of the rat reproductive and developmental studies.

Dosing of pregnant females with PFAAs results in gestational exposure to the fetus and also to the offspring during lactation. Cross-fostering studies of PFOA (White et al. 2009) and PFOS (Luebker et al. 2005) in which dosed dams fostered pups from control dams and vice versa showed that effects such as delayed development can result from exposures during either gestation or lactation.

Although malformations have been reported in a few rodent studies of PFOA and PFOS, effects such as full litter resorptions, decreased litter or number of live pups at birth, decreased survival of neonates, and decreased fetal and neonatal weight have been more frequently and consistently found (USEPA 2023, 2023). These developmental effects may result from toxicity to the placenta, as has been observed for PFOA (Suh et al. 2011) and PFOS (Lee et al. 2015). With PFOS at relatively high doses, neonatal mice and rats appeared normal at birth but died within a few hours; the genesis of this phenomenon is not understood (multiple studies reviewed in NJDWQI 2018).

Decreased growth of offspring and/or delays in reaching developmental milestones was observed for several PFAS in rodent studies (Table 17-8 Toxicological Effects Excel file). For PFBS (Feng et al. 2017) and PFNA (Das et al. 2015), body weight decrements persisted until adulthood. PFOA caused delays in ossification of bones and eruption of teeth (Lau et al. 2006; Yahia et al. 2010). Developmental markers such as eye opening and/or reaching sexual maturity were also delayed by some PFAAs, while noting that sexual maturity was conversely accelerated in male mice by PFOA (Lau et al. 2006). Persistent neurobehavioral effects in mice resulted from developmental exposures to several long-chain PFAS (Johansson, Eriksson, and Viberg 2009; Onishchenko et al. 2011; Lee and Viberg 2013).

Certain developmental effects of some PFAAs persisted into adulthood. These include decreased size of uterus and ovaries, accompanied by decreased number of follicles and corpora lutea, and changes in reproductive and thyroid hormone levels in female mouse offspring exposed to PFBS (Feng et al. 2017). Developmental exposures of mice to PFOA caused persistent delays in mammary gland development (White et al. 2009) and persistent liver toxicity (Quist et al. 2015) at doses lower than those that caused other systemic and developmental effects; these endpoints have not been evaluated for other PFAS.

17.2.5.3 Chronic Toxicity and Tumorigenicity

PFAAs have generally not been found to be mutagenic or genotoxic (Lau 2015). Of the PFAS included in Table 17-8 Toxicological Effects Excel file, chronic studies that evaluated carcinogenicity and other effects of long-term exposure have been conducted in rats only for PFHxA, PFOA (three studies; one in males only), PFOS, and GenX. PFHxA did not increase the incidence of tumors in either sex of rats. PFOA increased the incidence of several types of tumors, including testicular Leydig cell adenomas in two of the three studies, and hepatic adenomas and/or carcinomas and pancreatic acinar cell adenomas and/or carcinomas in two of the three studies, and uterine adenocarcinomas in one of the three studies. In the chronic PFOS study, pancreatic acinar carcinomas and benign tumors in other organs were increased, including hepatic adenomas in females, and thyroid follicular cell adenomas in males only in the high dose “recovery group” (dosed for the first year only and evaluated at the end of the 2-year study). GenX increased the incidence of both hepatocellular adenomas and carcinomas in females, and the incidence of combined pancreatic acinar cell adenomas and carcinomas and testicular Leydig cell adenomas in males.

IARC (2016) classified PFOA as “possibly carcinogenic to humans” (Group 2B) based on limited evidence that PFOA causes testicular and renal cancer, and limited evidence in experimental animals. IARC (2023) is currently reevaluating the classification of PFOA and evaluating PFOS for the first time. Based on the USEPA (2005) Guidelines for Carcinogen Risk Assessment, USEPA (2023, 2023, 2018) described PFOA and PFOS as likely human carcinogens, and GenX as having suggestive evidence for human carcinogenicity. A recent review by NJDWQI (2023) concurred with USEPA (2023) that PFOA is a likely human carcinogen; this review also concluded that PFOS has suggestive evidence but did not consider the USEPA (2023) evaluation that found a statistically significant trend for pancreatic acinar tumors in the chronic rat study (see Section 17.2.3.5). For PFOA, ATSDR (2018), draft concluded that the hepatic tumors are unlikely to be relevant to humans. In contrast, USEPA (2023) concluded that, in the “absence of definitive information supporting a single, scientifically justified mode of action (MOA) and “evidence supporting the potential for multiple plausible MOAs, … USEPA takes the health-protective approach and concludes that the hepatic tumors observed [in two chronic rat studies]… can be relevant to human health.” Human relevance was not discounted for the testicular and pancreatic tumors by either ATSDR (2018) or USEPA (2023). For PFOS, USEPA (2023) and NJDWQI (2018) did not discount human relevance of the hepatic tumors. NJDWQI (2017) developed cancer slope (potency) factors for PFOA based on the incidence of testicular Leydig cell tumors in rats, while the California EPA (CA OEHHA 2023) and USEPA (2023) slope factors are based on the incidence of kidney cancer in humans and are much more stringent than PFOA slope factors based on animal data. NJDWQI (2018) and USEPA (2023)) both developed cancer slope factors for PFOS based on the incidence of liver tumors in rats.

17.2.6 Health Effects Information for Some Additional PFAS of Current Interest

17.2.6.1 Information Relevant to Human Health Effects of Ether and Polyether PFAS

There is increasing awareness and interest in potential human exposure to PFAS other than PFAAs. These include ether and polyether PFAS and dicarboxylic acid polyether PFAS used as replacements for long-chain PFAAs. Additionally, ether and polyether PFAS and PFAS with other structures can be formed as unintentional byproducts of industrial processes (Wang et al. 2019). Health effects information for hexafluoropropylene oxide dimer acid (HFPO-DA, GenX), a 6-carbon perfluoroether, and ADONA, a 7-carbon polyfluoropolyether, which are both used as replacements for PFOA, is discussed in Sections 7.1.4 and 17.2.5. Information on the environmental occurrence, ecological effects, toxicology and toxicokinetics in laboratory animals, and bioaccumulation and potential health effects in humans is currently becoming available for additional non-PFAA PFAS at a rapid pace, particularly for additional ether and polyether PFAS (Wang et al. 2019). Collectively, this information indicates that the toxicological and bioaccumulative properties of some of these ether and polyether PFAS, particularly those with longer total chain lengths (carbons plus ether oxygens in the chain), are similar to those of the phased out long-chain PFAAs (for example, PFOA, PFOS, PFNA) (see Figure 2-4).

This section summarizes the currently available laboratory animal and human studies that are relevant to human health effects of some additional ether and polyether PFAS. This material expands the discussion of these groups of compounds beyond HFPO-DA (GenX) and ADONA that were discussed in Section 17.2.5. These additional ether and polyether PFAS include:

- per- and polyfluoroether carboxylates (PFECAs)
- per- and polyfluoropolyether carboxylates (PFPECAs)
- per- and polyfluoroether sulfonates (PFESAs)
- per- and polyfluoropolyether sulfonates (PFPESAs)

As discussed below, some of the most thoroughly studied PFESAs and PFPECAs have chlorine atoms on the terminal carbon (ClPFESAs and ClPFPECAs, respectively). Toxicity data for dicarboxylic acid PFPECAs are also discussed. Specifically, longer chain PFPECA analogues of GenX (HFPO-DA), including hexafluoropropylene oxide-trimer acid (HFPO-TA) and hexafluoropropylene oxide-tetramer acid (HFPO-TeA), and numerous other PFPECAs of various structures and chain lengths are of interest because they are used as replacements for phased-out long-chain PFAAs and/or formed as industrial byproducts. Many of these PFPECAs have been detected in the environment, including in drinking water in some cases (Pan et al. 2019; Munoz et al. 2019; Wang et al. 2019; Kotlarz et al. 2020). Industrial mixtures of ClPFPECAs of various chain lengths, as well as dicarboxylic acid polyether PFPECAs, are also of interest because they are used as alternatives for phased-out long-chain PFCAs, including PFNA (NJDEP 2021; Wang et al. 2013), and ClPFPECAs have been detected in environmental media near industrial sources (McCord et al. 2020; Washington et al. 2020; Mazzoni et al. 2015).

F53B is a PFOS alternative that consists primarily of 6:2 chlorinated polyfluoroether sulfonate (6:2 ClPFESA), with smaller proportions of 8:2- and longer chain ClPFESAs (Munoz et al. 2019; see also Section 2.6.1.3). These ClPFESAs are used primarily in China, and are of interest because they have been found in multiple environmental media and, as discussed below, in human biomonitoring studies. Nafion byproducts are PFPESAs formed as industrial byproducts in the production of Nafion, a sulfonated tetrafluoroethylene-based fluoropolymer-copolymer, and are of interest because they have been found in drinking water impacted by industrial discharges (Hopkins et al. 2018). With some exceptions, the toxicity and bioaccumulative potential of PFAAs with similar structures (for example, PFCAs, PFSAs) generally increase with increasing carbon chain length (see Section 7.1.4). Similarly, currently available information on the ether and polyether PFAS with analogous structures (for example, HFPO-DA, -TA, -TeA; 6:2 and 8:2 ClPFESA) discussed in this section suggests that their toxicity and bioaccumulation also generally increase with increasing chain length (including both carbons and ether oxygens).

Human Biomonitoring and Health Effects Studies

PFECAs and PFPECAs

As discussed below, recent biomonitoring studies show that, as is the case for long-chain PFAAs, many ether and polyether PFAS are bioaccumulative in humans, although this may not be the case for some shorter chain members of this group such as GenX (HFPO-DA). Associations with changes in health-related endpoints (for example, clinical chemistry parameters) were also reported in some studies.

A biomonitoring study of Wilmington, NC, residents evaluated blood serum PFAS levels 5 months after cessation of exposure to drinking water from the Cape Fear River that was contaminated by multiple PFAS. Nafion byproduct 2 and two longer chain PFPECAs were detected in the blood serum of >85% of subjects; two other fluoroethers were less frequently detected. The shorter chain PFECA, GenX (HFPO-DA), which was also present in drinking water, and several other PFAS that were detected in the Cape Fear River, were not found in human serum (Kotlarz et al. 2020). This study did not evaluate potential associations of health effects and exposure to fluoroethers. Yao et al. (2020), whose study population lived near a fluorochemical plant in China, also detected multiple PFECAs and PFPECAs, as well as sulfonate ether PFAS (discussed below), in blood serum. They reported associations between PFO5DoA, a long-chain PFPECA that has 7 carbons and 5 ether oxygens, and increased serum lipids, liver enzymes, and uric acid. Two other PFECAs (HFPO-TA, 9 carbons and 2 ether oxygens; PFO4DA, 6 carbons and 4 ether oxygens) were associated with increases in one or more serum lipid parameters, and PFO4DA was also associated with increased uric acid.

A summary of an unpublished biomonitoring study of workers with occupational exposure to industrial mixtures of ClPFPECA congeners of various chain lengths reported an estimated human half-life of 2.5–3 years. Associations with increased serum lipids, liver enzymes, triglycerides, albumin, albumin/globulin ratio, thyroid stimulating hormone (TSH), free thyroxine, and prostate-specific antigen (PSA), and decreases in estradiol and indicators of immune system function (alpha-2-globulins and immunoglobulins) were reported (Solvay 2019). It was noted that the changes in serum lipids and liver enzymes may have been confounded by exposure to PFOA, and that associations with increased TSH and PSA were less reliable because they were based on fewer data points (Solvay 2019).

PFESAs and PFPECAs

6:2 ClPFESA was consistently detected in human blood serum in several recent biomonitoring studies in China (Jin et al. 2020; Liu et al. 2020; Pan et al. 2017; Yao et al. 2020). The median and mean human half-life of 6:2 ClPFESA were estimated as 15.3 and 18.5 years, respectively, as compared to an estimated median and mean of 6.7 and 7.7 years, respectively, for PFOS in the same study (Shi et al. 2016). 6:2 ClPFPESA was included in the suite of PFAS measured in blood serum of U.S residents in NHANES for the first time in 2017–18 (CDC 2022). It was found at the detection limit (0.100 ng/ml) in the 95th percentile of the total population, and at the same or similar levels in most racial/ethnic groups as follows: Mexican Americans – not detected at 90th percentile, 0.100 at 95th percentile; non-Hispanic blacks – 0.100 ng/ml at 90th and 95th percentiles; non-Hispanic whites – not detected at 95th percentile; all Hispanics – not detected at 90th percentile, 0.100 at 95th percentile [values are geometric means]. The maximum level detected in any of these subgroups was 0.200 ng/ml. However, it was detected more frequently and at higher levels in Asians (0.200 ng/ml at 75th percentile; 1.00 ng/ml at 90th percentile; 2.30 ng/ml at 95th percentile; maximum – 10.9 ng/ml). It is not known whether the more frequent detections and higher serum levels in Asians results from their exposure while in Asia or from other sources such as consumption of foods contaminated with 6:2 ClPFESA that are imported from Asia.

As is the case for long-chain PFAAs, biomonitoring data demonstrate exposure to ClPFESAs in utero and through breast milk. Both 6:2 and 8:2 ClPFESA were found in matched maternal:umbilical cord blood samples, indicating fetal exposure, with 8:2 ClPFESA having a higher rate of transfer to cord blood (Cai et al. 2020; Chen et al. 2017; Pan et al. 2017; Xu et al. 2019). The only study that evaluated potential health outcomes associated with fetal exposure found no evidence of an association between ClPFPESAs exposure and birth outcomes (Xu et al. 2019). 6:2 and 8:2 PFESA were also found in human breast milk from several locations in China, but not from Sweden (Awad et al. 2020; Jin et al. 2020). Breast milk levels of these PFESAs were associated with decreased infant growth in one of these studies (Jin et al. 2020).

Rodent Toxicology Studies

PFECAs and PFPECAs

As discussed above, hepatotoxicity is an effect common to many PFAS. In mouse studies, HFPO-TeA, with 12 carbons and 3 ether oxygens, was more hepatotoxic than its shorter chain analogue HFPO-DA (GenX; Wang et al. 2017), and HFPO-TA, with 9 carbons and 2 ether oxygens, was more hepatotoxic than PFOA, which has an 8-carbon chain (Sheng et al. 2018). In mice, the bioaccumulation in blood serum and liver increased with chain length for a series of PFPECAs with two to four O-CF2 groups, and only the largest PFAS, with four such groups (PFO4DA), caused increased liver weight at the doses tested (Guo et al. 2019). A recent study (Chen et al. 2021) reported half-lives in male mice of 24 hours for PFO4DA and 43 days for its larger homologue, PFO5DoA after a single intravenous dose. In a 140-day study of male mice, both compounds accumulated in the liver and caused increases in body weight, relative liver weight, and serum glucose, triglycerides and free fatty acids, as well as biochemical changes in the liver consistent with reduced glycolysis (Chen et al. 2021).

As reviewed in NJDEP 2021, industrial products consisting of mixtures of ClPFPECA congeners of various chain lengths ranging from 8 carbons and 3 ether oxygens to 14 or 17 carbons and 5 ether oxygens caused toxicity to liver, lung, thymus, seminal vesicles, and thyroid in 4-week and/or 13-week rat studies, with some changes persisting after a several-week recovery period (Research Toxicology Centre 2006, 2016). The doses at which hepatic effects occurred were similar to those reported for long chain PFCAs (for example, PFOA, PFNA; NJDWQI 2015, 2017). The half-lives for five of the congeners (ranging from 8 carbons and 3 ether oxygens to 14 carbons and 5 ether oxygens) were reported as 8–29 days in male rats and 1.6–91 days in female rats. These half-lives are similar to those documented for PFOA (4-6 days) and PFNA (30 days) in male rats (Table 17-7).

Additionally, industrial products consisting of mixtures of another type of PFPECAs, dicarboxylic acid polyether carboxylates (chain lengths not specified), caused toxicity to the liver, lung, thymus, seminal vesicles, and kidneys, with hepatic effects at very low doses, in 4- and/or 13-week studies in rats. As for the ClPFPFECAs, some effects persisted after a several week recovery period. The estimated half-life in male rats after a single dose was 43 days, and the estimated half-lives after repeated dosing were approximately 8 days in males and 11 days in females (Research Toxicology Centre, 2005; Research Toxicology Centre, 2006). In contrast, PFOA and PFNA, with half-lives of 2-4 hours and 1-2 days, respectively, as well as some other PFAS, are much less persistent in female rats (Section 17.2.3; Table 17-7).

PFESAs and PFPESAs

6:2 ClPFESA, the primary component of F53B, and Nafion byproduct 2, also a PFPESA, caused liver toxicity in mice (Zhang et al. 2018; Lang et al. 2020). In a subchronic study of reproductive toxicity of 6:2 ClPFESA in male mice, relative weights of reproductive organs decreased at the highest dose tested. However, at the doses used in the study, there were no histopathological changes in these organs, and hormone levels, sperm counts, fertility, and expression of several testicular genes were not affected (Zhou et al. 2018). After subchronic exposure to mice, 6:2 ClPFESA accumulated in the small and large intestine, damaged the gut barrier, and caused inflammation of the colon (Pan et al. 2019).

Zebrafish Studies

Zebrafish are well accepted as an in vivo model system for human health effects. Zebrafish studies for the ether and polyether PFAS are relevant to evaluation of their potential human health effects and are discussed below.

PFECAs and PFPECAs

The hexafluoropropyl acids—HFPO-DA, HFPO-TA, and HFPO-TeA—caused estrogenic effects in zebrafish (Xin et al. 2019). A suite of PFPECAs of various chain lengths decreased thyroid hormone levels in developing zebrafish embryos, leading to thyroid hormone-dependent malformations of the swim bladder (Wang et al. 2020).

6:2 ClPFECA

A number of studies have reported toxic effects of 6:2 ClPFECA in zebrafish. These include: bioaccumulation in larvae and adults (Wu et al. 2019); hepatoxicity, in adults (Shi et al. 2019; Wu et al. 2019); reproductive toxicity in a two-generation study (Shi et al. 2018); disruption of cardiac development (Shi et al. 2017); and thyroid toxicity from developmental exposures to environmentally relevant concentrations (Deng et al. 2018) and in unexposed offspring after exposure of the parental generation (Shi et al. 2019). Tu et al. (2019) reported that 6:2 ClPFECA was more bioaccumulative and was a more potent disruptor of metabolism than PFOA in zebrafish.

17.2.6.2 Fluorotelomer Alcohols

Fluorotelomer alcohols (FTOHs) are polyfluoroalkyl substances synthesized as intermediates for the manufacture of various fluorosurfactants and fluoropolymers (Dinglasan-Panlilio and Mabury 2006; ECHA 2012). The telomer alcohols are named with the number of fully fluorinated carbon atoms first, followed by the number of partially fluorinated carbon atoms (for example, 8:2 FTOH, 6:2 FTOH). In the environment, FTOHs may degrade to PFCAs with 8:2 FTOH degradation capable of forming PFOA and PFNA (Butt, Muir and Mabury 2014). FTOHs are present in multiple consumer products, with 6:2 FTOH the primary FTOH manufactured for end use. Humans may be exposed by ingestion of FTOH-contaminated food or dust (Yuan et al. 2016). Some FTOHs are volatile, and human exposure may also occur via inhalation (Huang et al. 2019).

The following section summarizes currently available information on the toxicokinetics and adverse health effects of 6:2 and 8:2 fluorotelomer alcohol (6:2 and 8:2 FTOH, respectively) in experimental animals and humans. No peer-reviewed data were identified for other FTOHs.

Toxicokinetics

As polyfluoroalkyl substances, FTOHs are extensively metabolized in rodents and humans. Depending on the specific FTOH, the terminal metabolites include long- and/or short-chain PFCAs, unsaturated fluorotelomer acids (FTUCAs), fluorotelomer acids (FTAs) and glutathione, sulfate, and glucuronide conjugates (Kudo et al. 2005; Fasano et al. 2006, 2009; Himmelstein et al. 2012; ECHA 2012; Nilsson et al. 2013; Kabadi et al. 2018; Huang et al. 2019; Rice et al. 2020).

6:2 FTOH is rapidly absorbed following oral exposure, and undergoes metabolism in rats to form PFBA, PFPeA, PFHxA, PFHpA, certain FTAs, and glutathione, sulfate, and glucuronide conjugates (Russell et al. 2015; Kabadi et al. 2018). In vitro metabolic data from hepatocyte cultures indicate that 6:2 FTOH is likely metabolized similarly in rat, mice, and humans (reviewed in Rice et al. 2020). One of the non-PFCA metabolites, 5:3 FTA, is persistent, having an estimated half-life of ~100 days in male and female rats after repeated dosing (Kabadi et al. 2020). Russell et al. (2015) calculated an apparent geometric mean elimination half-life of 43 days for 5:3 FTA in humans based on occupational data of Nilsson et al. (2010, 2010, 2013). PFHxA and the other terminally stable short-chain PFCAs formed by the metabolism of 6:2 FTOH do not undergo further degradation and are eliminated rapidly in rodents (see Table 17-7). The metabolic pathways, rate determining steps, and elimination half-lives of the parent 6:2 FTOH and other metabolites have not been established.

8:2 FTOH administered orally or by inhalation is also rapidly absorbed and metabolized in rats and mice, with PFOA, 7:3 FTA, 8:2 FTA, PFNA, PFHxA, PFHpA, and glucuronide, glutathione, and other conjugates identified as metabolites (Kudo et al. 2005; Fasano et al. 2006, 2009; Himmelstein et al. 2012; ECHA 2012). In vitro data from rat, mouse, and human hepatocytes indicate that 8:2 FTOH is metabolized to PFOA in rodents and humans, although rodent hepatocytes appear to transform greater amounts of 8:2 FTOH to PFOA than human hepatocytes. Other in vitro metabolites in rodent hepatocytes include 8:2 FTCA, 8:2 FTUCA, and PFNA (ECHA 2012).

Data from the NTP (Huang et al. 2019) confirmed that 8:2 FTOH is rapidly absorbed and distributed in male and female rats after a single oral or intravenous (IV) dose. The plasma elimination half-life of the parent compound was 1.1–1.7 hours, and the two primary metabolites were 7:3 FTA and PFOA. The half-life of 7:3 FTA was 2–3 days in both sexes of rats; PFOA's half-life was sex-dependent (approximately 8–15 days in males, and 4.5–6.9 h in females). Nilsson et al. (2010, 2010) measured a mixture of 6:2, 8:2, and 10:2 FTOH and other PFAS in the workplace air of ski wax technicians and subsequently documented the presence of PFOA, PFNA, PFDA, PFDoA, PFTDA, 5:3 FTA, and 7:3 FTA in all samples of the technicians' blood (Nilsson et al. 2013). The metabolites, 8:2 FTUCA and 10:2 FTUCA, were also detected in blood samples from multiple technicians. Although concentrations of 8:2 FTOH were several-fold higher than other PFAS in workplace air, the relative importance of 8:2 FTOH and 10:2 FTOH to the metabolic formation of PFOA, PFNA, other long-chain PFCAs, or the FTAs cannot be determined from these data given that exposures were to multiple PFAS.

Toxicity

6:2 FTOH

Consistent with other data that have demonstrated a lack of genetic toxicity of PFAS (see Section 17.2.5.3), 6:2 FTOH was negative when tested in the Ames bacterial mutagenesis assay. It was not mutagenic in the mouse lymphoma assay and was not clastogenic in a chromosome aberration assay in human lymphocytes. It was found not to be a skin or eye irritant (Serex et al. 2014).

Given the metabolic transformation of 6:2 FTOH and 8:2 FTOH to several PFCAs, 5:3 FTA (6:2 FTOH metabolite), and multiple additional metabolites of unknown toxicity, it is unclear whether adverse effects associated with exposure of experimental animals to FTOHs (see following) are attributable to the parent FTOH, one or more metabolites, or to combined exposure to multiple compounds. With the exception of the persistent 5:3 FTA metabolite of 6:2 FTOH, for which limited data demonstrating toxicity are available (Rice et al. 2020), the relationship between the adverse effects of FTOHs and their metabolites has not been established.

Rice et al. (2020) synthesized toxicity data on 6:2 FTOH from a 28-day NTP study, a number of peer-reviewed publications (Miyata et al. 2007; Kirkpatrick 2005; O'Connor et al. 2014; Serex et al. 2014; Mukerji et al. 2015), and OECD-compliant studies submitted on behalf of FTOH manufacturers. These studies reported that 6:2 FTOH causes multiple effects in the liver (for example, increased serum liver enzymes, hepatocellular necrosis, and oval cell hyperplasia) and kidney (renal tubular necrosis, mineralization, and degeneration) in rats and mice, as well as decreased thymus weight in rats. Reproductive effects of 6:2 FTOH in rats were observed only when high maternal mortality occurred. In contrast, 6:2 FTOH caused decreased body weight gain during lactation, mammary gland lesions, decreased uterine and ovarian weights, and an increase in anestrus in mice. 6:2 FTOH elicited developmental effects in both rats and mice, including increased pup mortality, delayed skull ossification, decreased pup body weight gain in rats, and decreased pup survival during lactation in mice.

Rice et al. (2020) also summarized the results of a 2-week oral toxicity study of the persistent 6:2 FTOH metabolite 5:3 FTA as reported by the industrial manufacturer. Those data indicate that in rats, 5:3 FTA caused adverse effects on the liver (decrease in total cholesterol, hepatocyte necrosis); kidney (increase in creatinine and urine volume, decrease in total urine protein); thyroid (follicular cell hyperplasia); and thymus (decrease in thymus weight).

There are no publicly available chronic toxicity studies for 6:2 FTOH.

8:2 FTOH

8:2 FTOH was negative when tested in the Ames bacterial mutagenicity study (NTP 2018), and in micronucleus assays reported by the OECD (ECHA 2012).

The liver and kidney were the primary target organs in rats administered 8:2 FTOH orally over a 90-day period (Ladics et al. 2008). 8:2 FTOH caused hepatic necrosis in males, and induced kidney nephropathy in females. Urinary and/or plasma fluorine levels were elevated in animals from all dose groups, an effect attributed to metabolism of the parent compound and an associated increase in fluoride levels. Wang et al. (2019) also documented effects of 8:2 FTOH on the livers of mice, including cellular vacuolation and swelling; swelling of cell nuclei; and immune cell infiltration in animals exposed orally for 28 days. 8:2 FTOH significantly altered mRNA levels of inflammatory cytokines in the thymus and spleen, although it is unclear whether these changes would translate to biologically significant effects on the immune system, as there were no accompanying histological changes in these organs.

Mylchreest et al. (2005) assessed the developmental toxicity of 8:2 FTOH in rats, finding that increased skeletal malformations in pups (delayed pelvic bone ossification and wavy ribs) occurred only at a dose that also elicited maternal toxicity. Mylchreest et al. (2005) also evaluated the reproductive and developmental toxicity of a commercial mixture of FTOH in rats, and observed decreases in litter size, pup weights, and the number of live pups per litter on days 0 and 4 of lactation. Developmental effects were seen only at a dose that also caused maternal toxicity.

There are no publicly available chronic toxicity studies for 8:2 FTOH.

17.2.6.3 Fluorotelomer Sulfonic Acids

Fluorotelomer sulfonic acids (FTSAs) and their salts, the fluorotelomer sulfonates (FTS), are polyfluorinated chemicals that are formed both by direct manufacture and by the degradation of precursors found in certain AFFFs or other industrial products (see Section 2.2.4.1; Field and Seow 2017). Because FTSAs and FTSs exist in anionic form in the body, they are equivalent toxicologically, and the term FTSA is used here to refer to both forms of these chemicals.

4:2 FTSA, 6:2 FTSA, and 8:2 FTSA have been detected in human blood (Lee and Mabury, 2011; Loi et al. 2013; Yeung and Mabry 2016; Eriksson et al. 2017), and 6:2 FTSA and 8:2 FTSA can cross the human placenta (Yang et al. 2016). Humans may potentially be exposed to FTSAs through ingestion of contaminated drinking water or food, or by inhalation of dust (Field and Seow 2017). It is not known if the detection of FTSAs in human blood is due to direct exposure to the parent compounds or to indirect exposure to FTSA or precursors (Field and Seow 2017).

Toxicokinetics

Information on the toxicokinetics of FTSAs is limited. No studies have evaluated the absorption of FTS versus FTSA. Since FTS and FTSA exist in the same anionic form within the body, their toxicokinetics would not differ after absorption. ECHA (2018) provided summary information on a single rodent in vivo study that examined the disposition and metabolism of 6:2 FTSA (species and dose levels not given). Following a single oral dose of 6:2 FTSA, 65–68% of the parent compound was recovered in urine 4 days post-dosing, indicating that metabolism of the majority of the administered dose did not occur. However, because no data were provided on metabolite formation or elimination, many questions remain regarding the metabolism of 6:2 FTSA in animals. In vitro data from ECHA (2018) and Hoke et al. (2015) also suggested that 6:2 FTSA is not extensively metabolized in animals. When 6:2 FTSA was incubated with rat liver microsomal fractions for 2 hours (ECHA 2018) or with rainbow trout hepatocytes for 4 hours (Hoke et al. 2015), no metabolism was detected. FTSA may have the potential to bioaccumulate, in that substantial levels of FTSA were measured in the livers of mice administered FTSA for 28 days (Sheng et al. 2017). The potential of FTSA to bioaccumulate is supported by observations of Yan et al. (2014), who found comparable levels of the bioaccumulative PFOA in the serum and livers of mice exposed under the same experimental conditions used for FTSA by Sheng et al. (2017). In the few human biomonitoring studies that included 6:2 FTSA, it was detected infrequently. For example, the Biomonitoring California Asian/Pacific Islander Community Exposures Project reported no detections of 6:2 FTSA in 2016 (N=96) and FTSA was detected in only 3% of samples analyzed in 2017 (N=99) (LOD=0.05 ng/ml) (CA OEHHA 2020).

Toxicity

6:2 FTSA was not genotoxic in assays of bacterial mutagenesis, or in mammalian cell assays of DNA repair or damage, micronucleus formation, or chromosome aberrations (ECHA 2018).

ECHA (2018) reported the results of unpublished oral range-finding and reproductive toxicity studies in rats. The 14-day range-finding study identified a NOAEL of 10 mg/kg-d based on changes in body and kidney weights and clinical chemistry (creatinine and urea) in one or more dose and gender groups. In the 90-day reproductive toxicity study, 6:2 FTSA did not affect male or female fertility or reproductive performance, and there were no effects on the number of pups, or on pup survival, growth, or sex ratio. The NOAEL for reproductive effects was $\geq$ 45 mg/kg-d.

Adult male mice administered 6:2 FTSA at 5 mg/kg-d over 28 days exhibited increases in liver weight, hepatocellular hypertrophy, hepatocellular necrosis, and biochemical markers associated with liver inflammation. Serum levels of the liver enzyme AST, an indicator of liver damage, and albumin were also elevated, and histological evidence of liver necrosis was observed (Sheng et al. 2017).

17.2.7 PFAS Mixtures

This section provides a brief overview of current toxicity-based approaches for addressing mixtures of PFAS and currently available information on toxicity of PFAS mixtures. This is an active area of research.

17.2.7.1 Proposed Approaches, for Addressing Toxicity of PFAS Mixtures

Total Concentration Approach (Called Simple Additive Approach by Cousins et al. 2020)

In this approach, a single guideline concentration is applied to the total concentration of a specified set of PFAS. This approach is based on the assumption that all of the included PFAS have the same toxic effects and MOA, are equally potent, and their combined toxicity is additive. In the absence of complete information on toxicity and MOA for all of the selected PFAS, this approach has been applied as a conservative public health-protective science-policy strategy.

Examples of this approach are the drinking water guidelines of 20 ng/L (Vermont) and 70 ng/L (Connecticut) for the total concentration of five long-chain PFAAs (PFOA, PFNA, PFHpA, PFOS, PFHxS) and 20 ng/L (Massachusetts) for the total concentration of six long-chain PFAAs (PFOA, PFNA, PFHpA, PFOS, PFHxS, PFDA) (CT DPH 2016; Vermont DOH 2018; MA DEP 2019), as well as in several other nations (Cousins et al. 2020).

MA DEP (2019) provided a detailed rationale for their approach based on the sum of the six long-chain PFAS. They concluded that this approach is supported by similarities in chemical structures, toxicity values developed by other agencies, toxicological responses, and long serum half-lives for these six PFAS. PFHxA was also considered but was not included, because it has a shorter half-life and causes toxicity at higher doses than the PFAS that were included.

MA DEP (2019) used results of Bayesian benchmark dose (BBMD) modeling of data for thyroid effects (free thyroxine; fT4) and increased liver weight for five of the six PFAS from NTP 28-day rat toxicology studies (NTP 2019). Using PFOA as an index compound with a BBMD of 1, relative BBMDs for fT4 for the other PFAS ranged from 0.5 to 3 on a serum-level basis and 0.8 to 4 on a human equivalent dose (HED) basis. For an increase in liver weight, relative BBMDs based on both serum PFAS levels or HEDs ranged from 0.2 to 2. MA DEP (2019) considered these BBMDs to be sufficiently similar to assume equivalence of the five PFAS.

As discussed by MA DEP (2019), there is a lack of data on toxicological effects, potency, and half-life of PFHpA (the 7-carbon PFAA included in the Connecticut, Vermont, and Massachusetts approaches), and no toxicity values (for example, reference doses) have been developed. Although Massachusetts recognized that PFHpA’s half-life is likely shorter than for PFOA, they concluded that there are no data to develop a compound-specific or relative toxicity value for PFHpA, or to conclude that it is toxicologically dissimilar to PFOA. Based on “read-across,” (prediction of toxicity based on data from similar compounds) these states consider PFHpA to be equipotent to PFOA.

Hazard Index Approach

Human health risk assessment often uses a hazard index approach, first developed by USEPA (1989), to evaluate the potential cumulative noncancer toxicity from co-exposure to multiple contaminants (USEPA 1989). As discussed in Section 9.1.3.1, calculation of a hazard index is based on the assumption of dose additivity, but it does not necessarily require that the MOA or toxicological endpoint is the same for all components of the mixture. As discussed in USEPA (2023), the Hazard

Index approach can be based on a “general” Hazard Index, in which noncancer toxicity factors for multiple contaminants are used regardless of whether they are based on effects in the same or different target organs, or a “target organ specific” Hazard Index in which noncancer toxicity factors are based on effects in the same target organ. USEPA (2023) presented the basis for a proposed MCLG and MCL of a Hazard Index of 1 for mixtures of four PFAS (PFBS, PFHxS, PFNA, GenX). The draft MCLG and MCL use the “general” Hazard Index approach in which the Hazard Index considers toxicity values based on differing toxicological endpoints for evaluation of the toxicity of the mixture.

Health Canada (2018, 2018) has concluded that, although there are no in vivo studies of PFAS mixtures, the similarity in health effects of PFOA and PFOS support an assumption of dose additivity and thus support the use of a hazard index approach to address co-occurrence of PFOA and PFOS in drinking water. ATSDR has also applied the hazard index approach to evaluate potential risk from site-specific exposure to mixtures of several long-chain PFAAs, noting that their approach assumed dose additivity based on “toxicologic similarities” (ATSDR 2020).

Minnesota Department of Health (undated) uses a health risk index approach—similar to the target organ specific Hazard Index approach—to evaluate concurrent exposures to multiple chemicals in groundwater. It is based on grouping chemicals (including PFAS and others) that cause the same general type of adverse health effect (i.e., the same target organ—for example, thyroid, endocrine). In the Minnesota health risk index approach, multiple health endpoints may be considered for each individual contaminant.

Mumtaz et al. (2021) provided a “proof of concept” demonstration of the potential use of an ATSDR hazard index approach based on target organ toxicity doses (TTDs) for specific toxicological effects (endocrine, hepatic, reproductive, developmental, and/or immune) to assess the risks of PFOA, PFOS, tetrachlorodibenzo-p-dioxin (TCDD), and polybrominated diphenyl ethers (PBDEs). This approach is intended for use as a screening tool, with a hazard index of >1 for a specific effect indicating the need for further evaluation.

USEPA (2023) has recently proposed to regulate four PFAS (PFBS, PFHxS, PFNA, GenX) in drinking water based on the general Hazard Index approach.

Relative Potency Factor (RPF) Approach

In the RPF approach, each PFAS is assigned an RPF based on its potency compared to an index compound (for example, PFOA), which is assigned a potency factor of 1. The RPFs are applied to the concentration of each PFAS present in the mixture, and the toxicity of the total of the RPF-adjusted concentrations is assumed to be the same as the equivalent concentration of the index compound (for example, PFOA). See USEPA 2023 for more information about the RPF approach.

The RPF approach is based on dose additivity of the compounds that are included (see discussion in Hazard Index section above). The RPF approach (also known as the toxicity equivalency factor approach) has been adopted for several groups of chemicals known to cause toxicity through a common and well-defined MOA, including cholinesterase-inhibiting pesticides (organophosphates) and dioxins (PCDDs) and dioxin-like compounds (furans [PCDFs]; PCBs) that cause toxicity through activation of the AhR receptor.

The application of the RPF approach for risk assessment of PFAS mixtures is associated with greater uncertainty than for the groups of compounds noted in the preceding paragraph. In contrast to the groups of compounds discussed above, the range of adverse effects of PFAS is not due to a single specific MOA, such as activation of a specific receptor. Furthermore, the MOA may not be the same for all toxicological effects (for example, hepatic toxicity; developmental toxicity) and may vary among PFAS (discussed in this Mixtures section above).

Bil et al. (2021) proposed RPFs for 22 PFAS, with PFOA as the index compound. This is an extension of an earlier proposal of RPFs for 18 PFAS developed by RIVM (Netherlands National Institute for Public Health and the Environment) scientists (Zeilmaker et al. 2018). The RPFs were based on hepatic effects of PFOA and 15 other PFAS in male rats from studies with durations of 40–98 days. Hepatic effects in male rats were selected because these effects are common to many PFAS, and there is a large data set on these effects in male rats. Endpoints evaluated included relative liver weight (all 16 PFAS), absolute liver weight (15 PFAS), and hepatocellular hypertrophy (14 PFAS), and the final RPFs were based on relative liver weight because the data set was most complete. Relative liver weight data for all PFAS (based on external dose) were fit to parallel dose-response curves, which were determined to provide an acceptable fit to the data. BMDs for each PFAS for each effect were developed from the dose-response curves based on a 5% change in absolute or relative liver weight and a 10% change in the incidence of hepatocellular hypertrophy. RPFs were based on the ratio of the BMDs for each PFAS to the BMD for PFOA and ranged from 0.001 (PFBS) to 10 (PFNA). RPF ranges for seven additional PFAS for which no relevant data were available were estimated by read-across/interpolation.

In contrast, Peters and Gonzalez (2011) concluded that it is not appropriate to develop TEFs (similar to RPFs) for PFAS for reasons including differing modes of actions among PFAS. However, Bil et al. (2021) discussed that although the MOA for hepatic effects may differ among PFAS, the similarly shaped dose-response curves for these effects support the assumption of additivity and the application of RPFs for hepatic effects. They also note the need to determine whether the RPFs based on hepatic effects are applicable to other types of toxicity caused by PFAS, such as developmental and immune system effects—an analysis that has not yet been conducted. Goodrum et al. (2021) concluded that the shapes of the dose-response curves for hepatocellular hypertrophy for PFOS and PFHxS in male rats, based on administered dose, differ from the dose-response curves for this effect for other PFAAs. When based on internal dose (serum levels), the shape of the curve for PFHxS differed from the shape of the curves for the other long-chain PFAAs. These results suggest that PFHxS, and possibly PFOS, are not additive with other PFAAs for hepatocellular hypertrophy in male rats; curves for liver weight were not evaluated.

17.2.7.2 Toxicology Studies of Defined PFAS Mixtures

Only a few studies of the toxicity of mixtures of PFAS, including studies of defined mixtures (i.e., mixtures for which the identities and concentrations of the components are known) of PFAS and studies of complex mixtures (i.e., mixtures for which the identities and concentrations of the components are not fully characterized) of PFAS such as AFFF were located; these are summarized below. These include in vitro studies of nuclear receptor activation in cultured cells transfected with the receptor of interest, and toxicity in cultured cells, zebrafish (a model species for human toxicity), and rodents.

Mammalian Studies

Defined PFAS Mixtures

Several recent studies have evaluated effects of defined mixtures of PFAS in mammalian species. Marques et al. (2021) dosed pregnant mice fed either a standard lab diet or a high fat diet with 1 mg/kg/day PFOA, PFOS, or PFHxS, individually, or 1 mg/kg/day of all three PFAS, throughout gestation. The authors concluded that “the PFAS mixture had very distinct effects when compared to single compound treatment, suggesting cumulative properties of the mixture, particularly when evaluating PFAS transfer from dam to pup,” and that “these results suggest that there are multiple pathways in which PFAS could add, synergize, or antagonize specific effects, and warrants further investigation of dose response data with model predictions of additivity.” However, as noted by USEPA (2023), “these studies did not include individual PFAS dose response data or conduct any mixture model-based analyses, so it is not possible to ascertain if the mixtures behaved in a dose additive or risk additive manner, or if interactions occurred.”

Roth et al. (2021) evaluated the effects of exposure to a mixture of PFOA, PFOS, PFNA, PFHxS, and GenX (2 mg/L each) in drinking water in mice fed a high fat diet. This treatment increased serum cholesterol, sterol metabolites, and bile acids, and caused liver toxicity, with some differences between males and females. However, the toxicological interactions among PFAS in this study cannot be determined because effects of individual PFAS were not evaluated.

Conley et al. (2022) evaluated the dose-response curves for range of effects in rat dams and their offspring from dosing with PFOA and PFOS alone and in combination during gestation and early lactation. Mixtures of PFOA and PFOS caused effects at lower doses compared to PFOA alone for endpoints including decreased offspring survival; maternal and offspring body weight; offspring serum T3 and glucose; and increased maternal kidney weight; maternal and offspring liver weight; and offspring bile acids, BUN, and bilirubin. Histopathological changes were observed in maternal liver and kidney and offspring liver after exposure to the mixture. The effect of co-exposure to PFOA and PFOS for effects in dams and offspring was consistent with dose additivity, with the exception of maternal body weight at term and gestational weight gain, which were less than additive. USEPA (2023) stated that “this work is ongoing with multiple KE analyses still to be conducted on samples collected during the studies. However, results thus far support the hypothesis of joint toxicity on shared endpoints from PFOA and PFOS co-exposure, and dose additivity as a reasonable assumption for predicting mixture effects of co-occurring PFAS.”

Complex Mixtures—AFFF

McDonough et al. (2020) evaluated several endpoints in mice associated with exposures to a commercial AFFF formulation containing known concentrations of PFOS and PFOA. The results were compared to those from an unexposed control and another set exposed to a similar concentration of PFOA alone. The study identified elevated concentrations of several other perfluorosulfonic acids in the exposed mice compared to the controls, and statistically significant increases in liver mass. T-cell dependent antibody suppression in mice exposed to an AFFF dose, expressed as PFOS + PFOA, was comparable to that of an equivalent dose of PFOA alone, both of which were statistically significant in comparison to the control group. Blood serum analysis of the mice exposed to the AFFF showed that they had also been exposed to a range of perfluorosulfonic acids from PFPeS to PFDS, though PFHxs and PFOS were predominant.

Receptor Activation

As discussed in Section 17.2.5, an important MOA for many PFAS is activation of cellular receptors, including PPAR-α and others, that regulate expression of genes that control many biological pathways. Wolf et al. (2014) studied PPAR-α activation by PFOA, PFNA, PFHxA, PFOS, and PFHxS singly, and in binary mixtures of PFOA with each of the other four PFAAs using a cultured cell line transfected with the PPAR-α receptor. They concluded that there was additivity for PPAR-α activation in PFAS mixtures at concentrations up to 32 µM. An earlier study from the same research group used this test system with higher concentrations of PFAAs and found that PPAR-α activation in binary mixtures of PFOA, PFOS, PFNA, and PFHxS was antagonistic in the mixture of all four PFAS (Carr et al. 2013).

Activation of the estrogen and androgen receptors by PFOA, PFNA, PFDA, PFUnA, PFDoA, PFHxS, PFOS individually, and an equimolar mixture of all seven PFAAs, was evaluated in cultured cell lines transfected with these receptors (Kjeldsen and Bonefeld-Jorgensen 2013). The results of this study illustrated the complexity of interactions of mixtures of PFAS in regard to receptor activation. PFOA, PFOS, and PFHxS singly, as well as the mixture of the seven PFAAs, were weak agonists of the estrogen receptor and also enhanced activation by the endogenous estrogen, 17-beta estradiol. These three PFAS also inhibited activity of the androgen receptor, and the same three PFAS, as well as PFNA and PFDA, antagonized activation by the endogenous androgen, dihydrotestosterone. In contrast to some of the individual PFAAs, the PFAA mixture did not affect androgen receptor activity in the absence of dihydrotestosterone, but it did antagonize activation of the receptor by dihydrotestosterone. Comparison of the androgen receptor dose-response data for the inhibitory PFAAs and the mixture indicated a synergistic antagonistic effect (greater than additive inhibition) of the PFAAs in the mixture.

Nielsen et al. (2022) developed an in vitro system to predict the effects of defined PFAS mixtures on activation of human PPARα. They determined that PFCAs tended to act as full PPARα agonists and PFSAs tended to act as partial PPARα agonists, with individual PFAS differing in potency. Nielsen et al. (2022) also found that concentration additive approaches to predicting mixtures effects on PPARα may overpredict the effects of PFAS mixtures on PPARα activation.

Effects in Cultured Hepatocytes

Defined PFAS mixtures
The effects of PFHpA, PFOA, PFNA, PFDA, PFHxS, and PFOS individually, and in 11 binary and 4 ternary mixtures on cell viability of the human liver cell line, HepG2, were evaluated by Ojo et al. (2020). The concentrations that were tested for each PFAS were based on dilutions of the concentration that caused 50% loss of cell viability. Effects of many binary and ternary combinations were synergistic, while other combinations were antagonistic at some concentrations. PFOS was synergistic with the other five PFAS at almost all concentrations, while interactions in mixtures that included PFOA were either synergistic or antagonistic, with synergism predominating at lower concentration levels. In another study of the same cell line, PFOA and PFOS induced and promoted apoptosis, and a mixture of both PFAS showed additivity for this effect (Hu and Hu 2009).

Effects on gene expression of six individual PFAS (PFOA, PFNA, PFDA, PFDoA, PFOS, 8:2 FTOH) and four mixtures (PFOA plus PFOS; three mixtures of all six PFAS in different proportions) were evaluated in primary cultures of hepatocytes from rare minnow (Wei et al. 2009). No clear patterns of response were observed, in those mixtures of PFAS affected the expression of some genes that were not affected by individual PFAS, and vice versa.

Complex Mixtures—AFFF
Ojo et al. (2022) evaluated the toxicity of 24-hour exposure to varying concentrations of two historically used AFFFs containing PFAS in the HepG2 human liver cell line. PFAS in one of the AFFFs were primarily long- and short-chain PFAAs, while PFAS in the second AFFF were at lower concentrations and was primarily 6:2 FTS. Both AFFFs caused concentration-dependent decreases in cell viability and increases in two biochemical markers of toxicity; the AFFF containing PFAAs was more potent for these effects. Cellular DNA damage was induced only at the highest concentration tested (0.038%) of the AFFF containing PFAAs.

Zebrafish Studies

Defined PFAS mixtures

Fey et al. (2022) evaluated the effects of varying concentrations of PFOA and 6:2 FTS singly and as a mixture on mortality, hatching, and developmental endpoints in zebrafish. The authors concluded that the relative potencies of PFOS and 6:2 FTS in this study were not constant and varied at different concentrations of the test substances, and, therefore, dose additivity could not be assumed.

The lethality of PFOA, PFOS, and a mixture of both chemicals was studied in zebrafish embryos (Ding at al. 2013). The interaction between PFOA and PFOS was concentration-dependent, with additive, synergistic, antagonistic, and then synergistic effects observed as the proportion of PFOS was increased.

Behavioral effects in zebrafish embryos were evaluated for PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFBS, PFHxS, PFOS, and 6:2 FTSA individually, and with mixtures of equal concentrations of all nine PFAS (Menger et al. 2020). PFHpA, PFOA, PFNA, PFHxS, PFOS, and 6:2 FTSA alone, as well as the mixture, caused behavioral effects in tests of locomotor activity, while PFBA, PFHxA, and PFBS did not. Specific behavioral effects varied among individual PFAS. The mixture of PFAS was less potent than the individual PFAS present in the mixture, suggesting antagonistic interactions among the PFAS in the mixture.

17.2.7.3 Studies of Mixtures of PFAS and Contaminants Other than PFAS

Several additional studies evaluated toxicological interactions of individual PFAS with other environmental contaminants. In male mice, co-exposure to PFOS and PCB126 (a dioxin-like PCB) caused synergistic effects on hepatic expression of genes related to oxidative stress, inflammation, and atherogenesis; levels of a protein that is a biomarker for thrombosis and fibrosis (indicators of cardiovascular disease risk); and hepatic lipid levels. Co-exposure, but not the individual compounds, caused pathological changes indicative of liver injury.

The effects on gene expression in zebrafish embryos of PCB126 alone, PCB126 plus PFOS, PCB126 plus PFHxA, and PCB126 plus both PFOS and PFHxA were evaluated by Blanc et al. (2017). The PFAS were not tested in the absence of PCB126. PCB126 with both PFOS and PFHxA had a greater effect on the expression of several genes than PCB126 alone or PCB126 with PFOS or PFHxA individually. The results suggest synergistic effects of PFOS and PFHxA on the effects of PCB126 in this test system.

17.2.8 Evaluating PFAS Using New Approach Methodologies

In one of its most resource-intensive efforts on PFAS to date, the USEPA developed a screening library containing PFAS. This USEPA-curated list spanned several public-interest lists of PFAS, including those from the USEPA, United States Food and Drug Administration (FDA), Department of Defense (DOD), Agency for Toxic Substances and Disease Registry (ATSDR), Consumer Product Safety Commission (CPSC), and state regulatory agencies. The screening library was developed to support the development of analytical methods, environmental monitoring, and toxicity testing. Further information on the initial list of 430 PFAS is available on USEPA’s CompTox Chemicals Dashboard (USEPA 2020), which was developed by the USEPA’s Chemical Safety for Sustainability Research Program (USEPA 2020). The purpose of the dashboard, along with related databases and web applications developed by the agency, is to support the USEPA’s computational toxicology research efforts to develop new and innovative methods with the goal of incorporating advances in a wide variety of scientific disciplines (biology, biotechnology, chemistry, and computer science) to help identify important biological processes that may be disrupted by chemicals. Using computational toxicology research methods, it is hoped that thousands of chemicals can be rapidly evaluated for potential risk at small cost, and chemicals can be prioritized for further studies based on potential health risk information derived from this initial evaluation (USEPA 2020).

From the initial list of 430 PFAS (discussed above), a subset of 150 PFAS were chosen by USEPA with the overall goals of maximizing the ability to perform read-across (for example, predicting toxicity of a target PFAS compound by extrapolating such information from a PFAS compound that has been more extensively studied) and capturing structural diversity among PFAS. The USEPA also took into consideration likelihood of exposure or occurrence, and the availability of in vivo (mammalian) or in vitro (for example, cell culture) toxicity data for validation. Because compounds that exist as gases cannot be tested and some PFAS (for example, HFPO-DA [GenX]) rapidly degrade in dimethyl sulfoxide (DMSO), which is used as the vehicle in many of these assays (Liberatore et al. 2020), practical considerations such as the ability to procure in nongaseous form and to solubilize samples in the solvent DMSO without degradation were also considered (Patlewicz et al. 2019; USEPA 2020, 2020).

This group of 150 PFAS is also currently being evaluated at Oregon State University, the University of Pittsburgh, East Carolina University, and other institutions in a USEPA-funded effort to use in vivo and in vitro methods to systematically study PFAS toxicity. The goal of this research is to support the prioritization of PFAS in risk assessment and risk management

(USEPA 2019) by using a combination of in vivo toxicity screening assays and transcriptomics (evaluation of changes in RNA expression in specific tissues in response to biologic or environmental cues; these RNA molecules often code for proteins) in the zebrafish model to characterize the toxicity and pharmacokinetics of a range of volatile and nonvolatile PFAS. The subset of 150 PFAS is also being evaluated in in vitro assays intended to be predictive of various endpoints such as hepatotoxicity, developmental toxicity, immunotoxicity, neurotoxicity, mitochondrial toxicity, developmental neurotoxicity, endocrine disruption, and general toxicity (USEPA 2019). Results of these studies will be used to group PFAS by structures and biological activity. As mentioned above, the intent is to capture the structural diversity across the spectrum of PFAS of interest to USEPA and to support determination of the feasibility of read-across within structure-based groupings, an approach in which information from PFAS with extensive in vivo toxicity data could be used to predict toxicity of other PFAS that lack such data.

It is hoped that the results of these high throughput assays will (a) inform PFAS hazard characterization, (b) provide toxicokinetic information that may help predict disposition and excretion of PFAS from the body, and (c) prioritize PFAS for risk assessment and further in vivo mammalian testing that is needed for risk assessment. A further goal of this program is to determine, based on data for PFAS that have been evaluated in both in vitro and mammalian in vivo systems, whether the read-across approach can be used to support in vitro to in vivo extrapolation for estimation of oral equivalent exposures for PFAS (Fenton et al. 2020).

17.2.9 Data Gaps and Research Needs

Although many studies relevant to health effects of PFAAs have become available in the last few years, important data gaps remain for most of the PFAAs and PFECAs discussed here, as well as for many additional PFAS used in commerce or found in AFFF.

Human half-lives and other toxicokinetic data are not available for some PFAS found in drinking water and other environmental media. This information is critical for adequately assessing the bioaccumulative potential and relevant routes of exposure (for example, placental and breast milk transfer), and for extrapolation of animal toxicity information to humans.

Available data suggest that reactive intermediates can form in the metabolic pathways that convert PFAA precursors to PFAAs within the body. Additional information on the formation and potential toxicity of these reactive intermediates is needed.

Additional toxicology data are needed for some PFAAs found in environmental media, including drinking water. For example, there are very limited toxicology data for PFHpA, and no information was located for PFPeA. Additionally, although humans are exposed to multiple PFAS, very little toxicological data are available for mixtures of PFAS. Multigeneration studies are important for assessment of reproductive and developmental effects, and they are available for only a few PFAS. PFHxS is a PFAA with a long human half-life that has been found in human serum and in drinking water impacted by both industrial discharges and AFFF. Although developmental effects of PFHxS are of concern, there are currently no multigenerational developmental studies for PFHxS. Available information from rodent studies suggests that developmental exposures to some long-chain PFAS (PFOA, PFOS, PFHxS) cause permanent neurobehavioral effects, but these data are limited. Additional studies are needed on neurobehavioral effects of PFAS, particularly from early life exposure.

Studies that provide data on chronic effects, including carcinogenicity, are available for only four PFAS (PFHxA, PFOA, PFOS, GenX), and such studies are needed for PFHxS, PFNA, ADONA, and other PFAS to which humans may be exposed. All of the chronic studies were conducted in rats, and chronic studies in a second species such as mice would provide valuable information, particularly for those PFAS that are rapidly excreted in female rats.

The mode(s) of action for the toxicological effects of PFAAs are not fully understood and continue to be the focus of ongoing research. Although not the focus of this section, data on bioavailability of PFAS from environmental media other than drinking water (for example, soil) are limited, and such information can be useful in assessing exposures at contaminated sites.

Challenges related to the use of toxicity information from surrogates for PFAS for which no toxicity data are available are discussed in Section 9.1.1.2. There is a need to further develop and validate approaches for addressing groups and mixtures of PFAS, such as those described in Section 17.2.7.

Finally, OECD (2018) identified 4,730 PFAS-related CAS numbers, including compounds with many different structures, including some that have not been used commercially. The majority of these PFAS, including those in commercial use, have very limited or no toxicity data (Wang et al. 2015; Wang et al. 2017), indicating a critical data gap in health effects information for PFAS. The approaches currently under development at USEPA and the National Toxicology Program (NTP) that are discussed in Section 17.2.8 may prove useful for screening of a large number of PFAS with rapid assays that evaluate parameters related to toxicokinetics and toxicity (USEPA 2018). Additional information is found on the USEPA CompTox website (USEPA 2020; Williams et al. 2018) and from the NTP Rapid Evaluation and Assessment of Chemical Toxicity (REACT) Program (DeVito 2018). If this effort is successful, the results could be used, along with data on human exposure, for prioritization of PFAS for more detailed toxicological studies (USEPA 2018).

17.3 Additional Information for Risk Assessment

17.3.1 Human Health Exposure Assessment

Figure 9-5 illustrates predominant exposure pathways. In the following sections, summary information is presented for exposures by environmental medium. Information about site risk assessment is in Section 9. Information about PFAS occurrence in environmental media is discussed in Section 6. Links are provided to other sections for more details on related topics.

17.3.1.1 Soil

Soil exposure scenarios are possible at a site. Many PFAS are mobile and persistent in soil. As indicated in Section 5, PFAS distribution in soils is complex, reflecting several site-specific factors and individual PFAS-specific factors.

Sorption and retardation generally increase with increasing perfluoroalkyl tail length, and functional groups contribute to the degree to which a PFAS has the affinity to leach from soil to groundwater. A detailed discussion of the fate of PFAS in soil is provided in Section 5. Receptors, such as humans, terrestrial animals, and plants, in contact with soil containing PFAS may be exposed to the compounds.

PFAS may be absorbed through the skin; some relevant studies are summarized in Section 17.2.3 and by ATSDR (2021). Therefore, current evidence combined with existing toxicity factors suggest that dermal absorption from soils or associated groundwater is not expected to be an important exposure route for the general public compared to other exposure pathways, but may contribute to less significant exposures such as incidental ingestion of soils in combination with skin contact. Construction workers may contact PFAS in soils (if within the depth of construction activities).

17.3.1.2 Potable Water

Ingestion of PFAS-containing drinking water typically represents the dominant exposure pathway in comparison to ingestion of food or other exposure pathways especially when PFAS concentrations in drinking water reach a certain level (Post, Gleason, and Cooper 2017; Bartell 2017). However, the dominance of the drinking water pathway is relative and can be context specific as highly contaminated sources of food (e.g., fish or agricultural products) might result in significant exposure greater than that of water. As discussed and cited in Section 7.1.2, PFAS levels in young children (up to the age of 6) are often higher than in adolescents and adults consuming the same drinking water source (see also Section 17.2). This is most likely due to the relatively higher levels of water ingestion per unit of body mass at these ages. If bottled water is supplied for drinking water and food preparation purposes, potential exposures from potable water used for non-drinking water purposes (for example, showering, bathing, and hand-washing dishes) are expected to be minimal, with the possible exception of inhalation exposure to volatile PFAAs (see Section 17.3.1.6), which is not yet well characterized.

17.3.1.3 Groundwater

The same potential exposure pathways described above for potable water apply to groundwater when used as a potable source. As discussed for soils, construction workers may contact PFAS in shallow groundwater (if within the depth of construction activities), although dermal absorption potential from water is low. If PFAS-impacted groundwater is used as irrigation water for crops, homegrown produce, or animal watering, PFAS in groundwater may be transferred to biota (plants or animals), resulting in potential dietary exposures (see Section 17.3.3).

As indicated in Section 5.3, due to the mobility and persistence of PFAS in soil and groundwater, certain PFAS are expected to form larger plumes than certain less-soluble contaminants in the same hydrogeological setting. However, sorption and partitioning might restrict leaching rates from the vadose zone and reduce the advection-driven transport velocity of PFAS in groundwater, depending on specific properties of the PFAS. These processes might limit plume development and discharge to surface water and might provide time for transformation of PFAS precursors. Groundwater geochemistry can also affect the extent of biotic and abiotic transformation of PFAS precursors (Liu and Mejia Avendaño 2013).

17.3.1.4 Surface Water

Surface water impacted with PFAS by surface runoff or groundwater discharge also present possible exposures. Surface water exposures can occur through drinking water or by consuming aquatic biota from contaminated water bodies. Much of the PFAS reaching surface water tend to remain in solution, although there is likely to be partitioning to sediment and uptake to biota. Once in surface water, PFAS could contaminate groundwater through groundwater recharge (Liu et al. 2016; ATSDR 2008). See Section 16.2 for human health aspects of PFAS in surface water.

Biofilms on surface water are known to accumulate PFAS (Munoz et al. 2018), as do other organic-/protein-rich particles in aquatic systems (Ahrens and Bundshuh 2014). Therefore, surface water films that contain these matrices could be repositories (and potential sources of exposure), especially of long-chain PFAS. Similarly, PFAS-containing foams may form on certain surface waters and contribute to recreational exposures. PFAS-containing foam is discussed in Section 16.5.

17.3.1.5 Sediment

PFAS in surface runoff or groundwater discharge can partition to sediment and be taken up into biota. The exact processes that control affect sorption and bioavailability of PFAS in sediments are poorly understood and likely determined by several factors including the mixture of PFAS, salinity, and sediment composition (see Sections 6.5 and 5.3.4.2). Considerations for PFAS in sediments and the potential implications for human health risk assessment (for example, bioaccumulation into fish and recreational contact) are detailed in Sections 9.1 and 16.2.

17.3.1.6 Air

PFAS inhalation exposure scenarios are possible. Examples include dusts containing PFAS may be generated from a site where PFAS are present in soil, as well as aerosols derived from surface waters (Section 5.2.4). In addition, some PFAS (for example, FTOHs and some perfluoroalkyl sulfonamides) have higher volatilities and can partition into air from other media (Section 5.2.4). Certain PFAS are found in ambient air with elevated concentrations observed or expected in urban areas near emission sources, such as manufacturing facilities, wastewater treatment plants, fire training facilities, and landfills (Barton et al. 2006; Ahrens et al. 2011; Liu et al. 2015). See Section 6.1 for more information about PFAS occurrence in air.

17.3.1.7 Diet

PFAS exposures may occur from food consumption, such as ingesting aquatic and terrestrial plants and animals that have taken up PFAS. Crops may be impacted by PFAS if irrigated with contaminated groundwater or surface water; if impacted by soil, runoff, or atmospheric deposition; or where biosolids have been applied to soil. In addition, because some PFAS biomagnify in food webs, ingestion of contaminated biota, especially fish and animals that eat fish, may be an important exposure route (ATSDR 2020; ATSDR 2021; USEPA 2016; USEPA 2016). Recreationally caught fish from areas with PFAS contamination may be a specific source of elevated exposures to PFAS that bioaccumulate in fish. PFAS exposures may also occur from food packaging materials containing PFAS (see Section 17.3.1.8, Consumer Products).

Breast Milk and Infant Formula

Consumption of breast milk and infant formula are potential exposure scenarios for infants. Breast milk may be impacted from a lactating mother’s exposure to PFAS-contaminated media, and infants may ingest PFAS from formula prepared with PFAS-contaminated water (Fromme et al. 2010; Mogensen et al. 2015). Higher exposures to infants are of concern because infants are sensitive subpopulations for developmental effects of PFAS, as discussed in Section 7.1 and Section 17.2. Infants may have a higher level of exposure to PFAS through breast milk or formula prepared with contaminated water than adults typically have through consuming contaminated water due to differences in the volume of water consumed relative to body weight. The USEPA Exposure Factors Handbook (USEPA 2019) provides detailed information on breast milk consumption rates and the higher water consumption rate of infants.

17.3.1.8 Consumer Products

Typically, exposure scenarios associated with consumer products are not included in human health risk assessments (HHRAs) for contaminated sites. However, the HHRA should acknowledge that analytical results for environmental media (including indoor air and dust) may reflect impacts from consumer products (for example, carpets and upholstered furnishings) containing PFAS that have degraded, released fibers, or volatilized (see Section 2.5).

17.3.2 Other Considerations When Calculating Exposure Point Concentrations

Other contaminants present at the site can affect the movement of PFAS, which are not easily accounted for in fate and transport models. For example, petroleum hydrocarbon co-contaminants, particularly light nonaqueous phase liquids (LNAPLs), may affect the fate and transport of AFFF-derived PFAS (Guelfo and Higgins 2013; Lipson, Raine, and Webb 2013; McKenzie et al. 2016). As discussed in detail in Section 5 and Section 10.4, PFAS movement in environmental media depends on both site-specific media properties and properties of the specific PFAS. Leaching potential is a function of both media properties (for example, pH, redox conditions) and PFAS structural properties (for example, chain length) (Gellrich, Brunn, and Stahl 2013; Gellrich, Stahl, and Knepper 2012).

It is critically important to collect site-specific soil partitioning and soil-to-groundwater pathway data for PFAS sites. Existing models and standard methods are not able to accurately predict or calculate soil-to-groundwater movement of PFAS given their hydrophobic and hydrophilic properties. Therefore, site-specific empirical data are necessary.

As discussed in detail in Section 5.4, the composition of PFAS can change in media. Studies have reported both biotic and abiotic transformations of some polyfluorinated substances (precursors), which may form PFAAs (Buck et al. 2011). Precursors that are ingested can be transformed in the body to PFAAs (USEPA 2016; USEPA 2016). However, PFAAs likely do not degrade or otherwise transform under ambient environmental conditions. PFAS composition may also change in surface water because of biotic and abiotic degradation of PFAA precursors. These complex transformations are not incorporated in current fate and transport models.

17.3.3 Information about Selecting Bioaccumulation and Bioconcentration Factors

Certain PFAS can bioaccumulate in the food web including aquatic organisms (see Section 5.5 [PFAS Uptake into Aquatic Organisms] and Section 6.5.3 [Fish]), terrestrial animals (for example, livestock and wild game), as well as plants. PFAAs, particularly PFOS, are typically the dominant PFAS detected in biota (Houde et al. 2011). Section 5.5, 5.6, and Section 16 provide detailed discussions of factors affecting the bioaccumulation potential of PFAS across a variety of organisms.

Figure 17-1 illustrates bioaccumulation pathways from sediment and surface water.

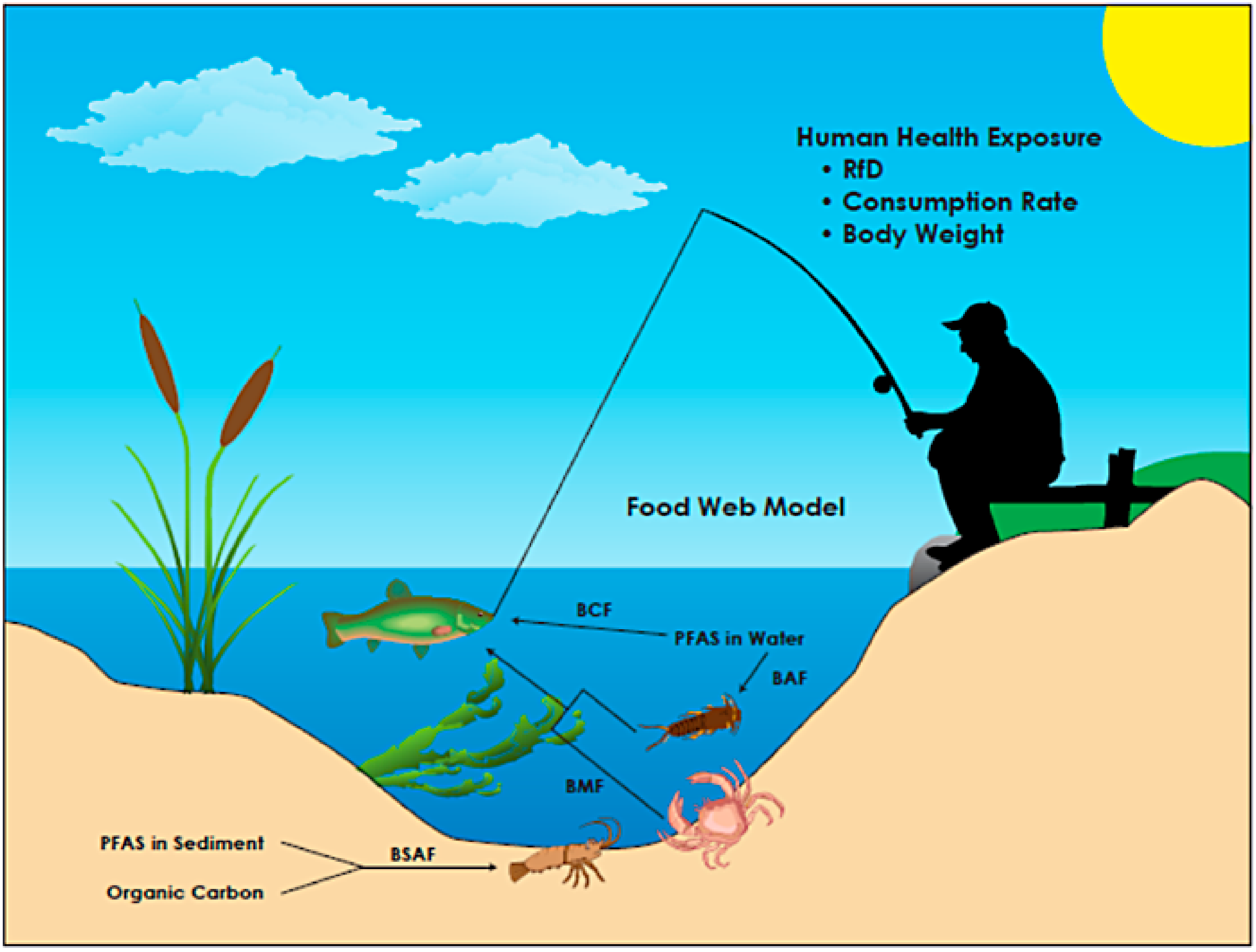


Figure 17-1. Bioaccumulation of PFAS from sediment and surface water. (BAF–bioaccumulation factor; BCF–bioconcentration factor; BSAF–biota-sediment accumulation factor; BMF–biomagnification factor; RfD–reference dose. *(Source: J. Conder, Geosyntec. Used with permission.)*

Section 6.5.3 (Fish) provides a detailed discussion of bioaccumulation of PFAS in fish. PFAS accumulation in fish has been documented, particularly for PFOS, longer chain PFCAs (with eight or more fluorinated carbons), and perfluorodecane sulfonate (PFDS) (Houde et al. 2011; Martin et al. 2013; Conder et al. 2008). In fish, PFOS tends to partition to the tissue of highest protein density, including the liver, blood serum, and kidney (Falk et al. 2015; Ng and Hungerbühler 2013). Available aquatic organism BCF and BAF data are presented in Table 5-1 (provided as a separate Excel file). Trophic level biomagnification in food webs (Figure 17-1) can occur for some PFAS (Franklin 2016; Fang et al. 2014) as discussed in further detail in Section 5.5.3.

Sections 5.6 and 6.5.1 discuss partitioning of PFAS to plants.

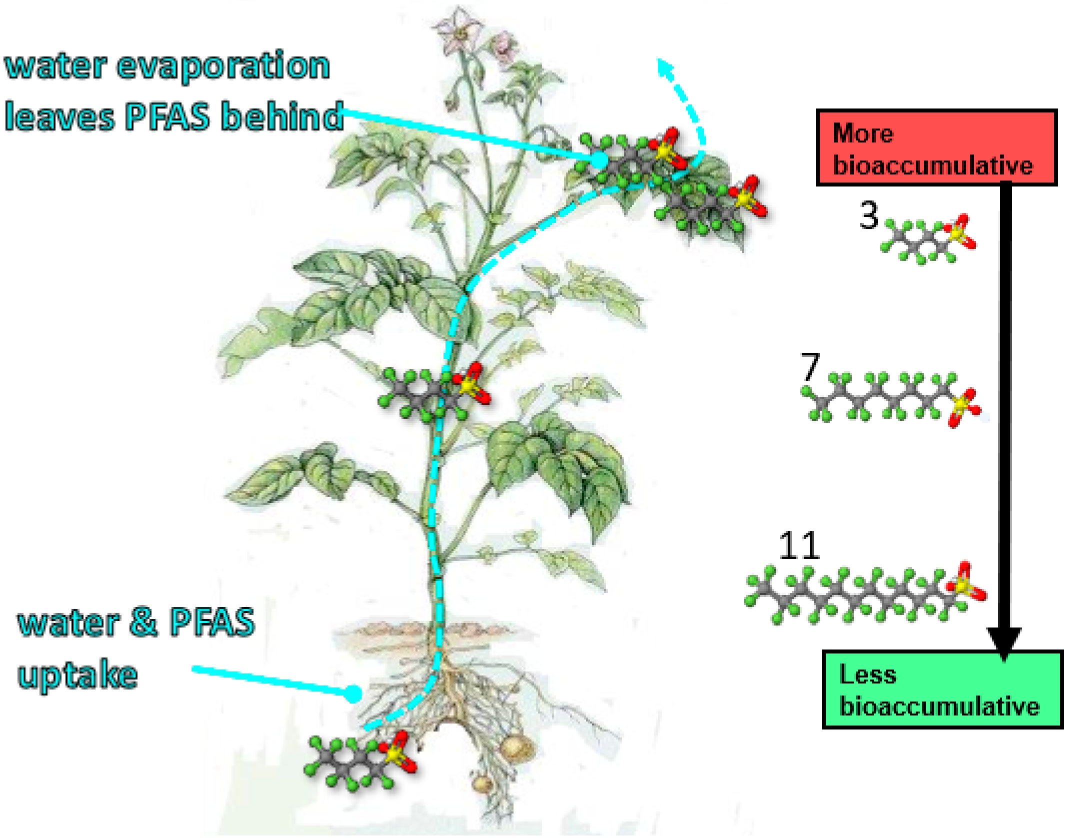


Figure 17-2. Bioaccumulation of PFAS in plants.

Source: J. Conder, Geosyntec. Used with permission.

Plant uptake, bioaccumulation, and partitioning within the plant appear to depend on PFAS chemical structure and the plant species. Figure 17-2 illustrates bioaccumulation of PFAS in plants. Most studies report partitioning of PFAAs within plants, with longer chain PFAAs, especially PFSAs, partitioning to the roots and more soluble, shorter chain PFAAs, especially PFCAs, partitioning to other parts of the plant (Lechner and Knapp 2011; Stahl et al. 2009) Blaine (Blaine et al. 2013; Blaine, Rich, Sedlacko, Hundal, et al. 2014; Yoo et al. 2011; Scher et al. 2018; Gobelius, Lewis, and Ahrens 2017). Table 5-2 (provided as a separate Excel file) contains BCFs and BAFs for various PFAS in a variety of plant species. In general, most plant BCFs and BAFs fall between a range of 0.1 and 10.

As indicated in Section 4.2.8 (Octanol/Water Partition Coefficient (K_{ow})) and Section 5.5.2 (Bioaccumulation), it is difficult to measure K_{ow} for PFAS due to their complex chemistry, and because many PFAS have both hydrophilic and hydrophobic properties. Therefore, BAFs rely on calculations from empirical data instead of modeling (Haukås et al. 2007).

Updated September 2023.

References

3M Company. 1999. “Fluorochemical Use, Distribution and Release Overview.” https://www.ag.state.mn.us/Office/Cases/3M/docs/PTX/PTX2754.pdf.

3M Company. 1999. The science of organic fluorochemistry. http://www.fluoridealert.org/pesticides/pfos.fr.final.docket.0006.pdf.

3M Company. 2000. Sulfonated Perfluorochemicals in the Environment: Sources, Dispersion, fate and Effects. St. Paul, MN. http://www.fluoridealert.org/wp-content/pesticides/pfos.fr.final.docket.0005.pdf.

3M Company. 2000. “Phase-out Plan for POSF-Based Products,”. https://www.regulations.gov/document?D=EPA-HQ-OPPT-2002-0051-0006.

3M Company. 2003. Environmental, Health and Safety Measures Relating to Perfluorooctanoic Acid And Its Salts (PFOA).

3M Company. 2006. 3M Production History: Perfluorooctanesulfonyl Fluoride (POSF). http://www.pops.int/documents/meetings/poprc/submissions/Comments_2006/3M.doc.

3M Company. 2007. Remedial investigation report. Phase 2. Fluorochemical (FC) data assessment report for the Cottage Grove. St. Paul, MN.

3M Company. 2017. About 3M AdMD Fluoropolymers.

3M Company. 2017. 3M and Fluorochemicals.

3M Company. 2018. “3MTM Fluorosurfactants.”. accessed 2021. https://tinyurl.com/3z497j8.

40 CFR 300.5. 2001. “Definitions.” accessed 2021. https://www.govinfo.gov/app/details/CFR-2001-title40-vol24/CFR-2001-title40-vol24-sec300-5.

40 CFR 300.400. 2019. “General.” accessed 2021. https://www.govinfo.gov/app/details/CFR-2019-title40-vol30/CFR-2019-title40-vol30-sec300-400.

Abbott, B. D., C. J. Wolf, K. P. Das, R. D. Zehr, J. E. Schmid, A. B. Lindstrom, M. J. Strynar, and C. Lau. 2009. “Developmental toxicity of perfluorooctane sulfonate (PFOS) is not dependent on expression of peroxisome proliferator activated receptor-alpha (PPAR alpha) in the mouse.” Reprod Toxicol 27 (3-4):258-265. https://doi.org/10.1016/j.reprotox.2008.05.061.

Abbott, B. D., C. J. Wolf, J. E. Schmid, K. P. Das, R. D. Zehr, L. Helfant, S. Nakayama, A. B. Lindstrom, M. J. Strynar, and C. Lau. 2007. “Perfluorooctanoic acid induced developmental toxicity in the mouse is dependent on expression of peroxisome proliferator activated receptor-alpha.” Toxicol Sci 98 (2):571-81. 10.1093/toxsci/kfm110.

Abdul-Kareem Al-Sofi, M. 2001. “Seawater desalination — SWCC experience and vision.” Desalination 135 (1):121-139. https://doi.org/10.1016/S0011-9164(01)00145-X.

Abercrombie, Sarah A., Chloe de Perre, Youn Jeong Choi, Brian J. Tornabene, Maria S. Sepúlveda, Linda S. Lee, and Jason T. Hoverman. 2019. “Larval amphibians rapidly bioaccumulate poly- and perfluoroalkyl substances.” Ecotoxicology and Environmental Safety 178:137-145. https://doi.org/10.1016/j.ecoenv.2019.04.022.

Abercrombie, Sarah A., Chloé de Perre, Michael Iacchetta, R. Wesley Flynn, Maria S. Sepúlveda, Linda S. Lee, and Jason T. Hoverman. 2021. “Sublethal Effects of Dermal Exposure to Poly- and Perfluoroalkyl Substances on Postmetamorphic Amphibians.” Environmental Toxicology and Chemistry 40 (3):717-726. https://doi.org/10.1002/etc.4711.

Abraham, Klaus, and Bernhard H. Monien. 2022. “Transdermal absorption of 13C4-perfluorooctanoic acid (13C4-PFOA) from a sunscreen in a male volunteer – What could be the contribution of cosmetics to the internal exposure of perfluoroalkyl substances (PFAS)?" Environment International 169:107549. https://doi.org/10.1016/j.envint.2022.107549.

ACRP. 2017. Use and Potential Impacts of AFFF Containing Per- and Polyfluoroalkyl Substances (PFASs) at Airports. http://www.trb.org/ACRP/Blurbs/175866.aspx.

ACS. 2016. "Teflon and Perfluorooctanoic Acid (PFOA)." American Cancer Society. https://www.cancer.org/cancer/cancer-causes/teflon-and-perfluorooctanoic-acid-pfoa.html.

Adamson, David T., Poonam R. Kulkarni, Anastasia Nickerson, Christopher P. Higgins, Jennifer Field, Trever Schwichtenberg, Charles Newell, and John J. Kornuc. 2022. "Characterization of relevant site-specific PFAS fate and transport processes at multiple AFFF sites." Environmental Advances 7:100167. https://doi.org/10.1016/j.envadv.2022.100167.

Adamson, David T., Anastasia Nickerson, Poonam R. Kulkarni, Christopher P. Higgins, Jovan Popovic, Jennifer Field, Alix Rodowa, Charles Newell, Phil DeBlanc, and John J. Kornuc. 2020. "Mass-Based, Field-Scale Demonstration of PFAS Retention within AFFF-Associated Source Areas." Environmental Science & Technology 54 (24):15768-15777. https://doi.org/10.1021/acs.est.0c04472.

AECOM. 2019. Unpublished Conceptual Illustration Showing "Surface Water Components within a Freshwater Environment".

Aerostar. 2019. Final Site Inspection Report of Aqueous Film Forming Foam Areas at Ellsworth Air Force Base Meade and Pennington Counties, South Dakota.

Aerostar SES. 2021. Final Remedial Design/Remedial Action Work Plan, FT002 at Clarks Marsh Interim Remedial Action, Former Wurtsmith Air Force Base, Oscada, Michigan. https://ar.afcec-cloud.af.mil/613354.pdf?token=AF0REiwNdKCWAvUDYB1quE3YWHTYHi8mfRNGPyMd_N41.

AFCEC. 2012. Monitoring and Remediation Optimization System (MAROS) Software, User's Guide and Technical Manual.

Ahmad, Mahtab, Anushka Upamali Rajapaksha, Jung Eun Lim, Ming Zhang, Nanthi Bolan, Dinesh Mohan, Meththika Vithanage, Sang Soo Lee, and Yong Sik Ok. 2014. "Biochar as a sorbent for contaminant management in soil and water: A review." Chemosphere 99:19-33. https://doi.org/10.1016/j.chemosphere.2013.10.071.

Ahmadireskety, Atiye, Bianca F. Da Silva, Jill A. Awkerman, Joe Aufmuth, Richard A. Yost, and John A. Bowden. 2021. "Per- and polyfluoroalkyl substances (PFAS) in sediments collected from the Pensacola Bay System watershed." Environmental Advances 5:100088. https://doi.org/10.1016/j.envadv.2021.100088.

Ahrens, Lutz. 2011. "Polyfluoroalkyl compounds in the aquatic environment: a review of their occurrence and fate." Journal of Environmental Monitoring 13 (1):20-31. 10.1039/C0EM00373E.

Ahrens, Lutz, Jonathan L. Barber, Zhiyong Xie, and Ralf Ebinghaus. 2009. "Longitudinal and Latitudinal Distribution of Perfluoroalkyl Compounds in the Surface Water of the Atlantic Ocean." Environmental Science & Technology 43 (9):3122-3127. https://doi.org/10.1021/es803507p.

Ahrens, L., and M. Bundschuh. 2014. "Fate and effects of poly- and perfluoroalkyl substances in the aquatic environment: A review." Environmental Toxicology and Chemistry 33 (9). 10.1002/etc.2663.

Ahrens, L., S. Felizeter, R. Sturm, Z. Xie, and R. Ebinghaus. 2009. "Polyfluorinated compounds in waste water treatment plant effluents and surface waters along the River Elbe, Germany." Marine Pollution Bulletin 58 (9):1326-1333. https://doi.org/10.1016/j.marpolbul.2009.04.028.

Ahrens, Lutz, Tom Harner, Mahiba Shoeib, Douglas A. Lane, and Jennifer G. Murphy. 2012. "Improved Characterization of Gas–Particle Partitioning for Per- and Polyfluoroalkyl Substances in the Atmosphere Using Annular Diffusion Denuder Samplers." Environmental Science & Technology 46 (13):7199-7206. https://doi.org/10.1021/es300898s.

Ahrens, L., J. Hedlund, W. Durig, R. Troger, and K. Wiberg. 2016. Screening of PFAS in Groundwater and Surface Water. Swedish Environmental Protection Agency.

http://naturvardsverket.diva-portal.org/smash/get/diva2:915446/FULLTEXT01.pdf.

Ahrens, Lutz, Dauren Mussabek, Kenneth M. Persson, and Ronny Berndtsson. 2019. “Temporal trends and sediment–water partitioning of per- and polyfluoroalkyl substances (PFAS) in lake sediment.” Chemosphere 227:624-629. https://doi.org/10.1016/j.chemosphere.2019.04.074.

Ahrens, L., J. Rakovic, S. Axelson, and R. Kallenborn. 2016. Source tracking and impact of per-and polyfluoroalkyl substances at Svalbard.: Swedish University of Agricultural Sciences.

Ahrens, L., M. Shoeib, T. Harner, D. Lane, R. Guo, and E.J. Reiner. 2011. “Comparison of Annular Diffusion Denuder and High-Volume Air Samplers for Measuring Per- and Polyfluoroalkyl Substances in the Atmosphere.” Analytical Chemistry 83 (24):9622-9628. https://doi.org/10.1021/ac202414w.

Ahrens, Lutz, Mahiba Shoeib, Tom Harner, Douglas A. Lane, Rui Guo, and Eric J. Reiner. 2012. “Correction to Comparison of Annular Diffusion Denuder and High Volume Air Samplers for Measuring Per- and Polyfluoroalkyl Substances in the Atmosphere.” Analytical Chemistry 84 (3):1797-1797. https://doi.org/10.1021/ac300035j.

Ahrens, Lutz, Mahiba Shoeib, Tom Harner, Sum Chi Lee, Rui Guo, and Eric J. Reiner. 2011. “Wastewater Treatment Plant and Landfills as Sources of Polyfluoroalkyl Compounds to the Atmosphere.” Environmental Science & Technology 45 (19):8098-8105. https://doi.org/10.1021/es1036173.

Ahrens, Lutz, Zhiyong Xie, and Ralf Ebinghaus. 2010. “Distribution of perfluoroalkyl compounds in seawater from Northern Europe, Atlantic Ocean, and Southern Ocean.” Chemosphere 78 (8):1011-1016. https://doi.org/10.1016/j.chemosphere.2009.11.038.

Ahrens, Lutz, Leo W. Y. Yeung, Sachi Taniyasu, Paul K. S. Lam, and Nobuyoshi Yamashita. 2011. “Partitioning of perfluorooctanoate (PFOA), perfluorooctane sulfonate (PFOS) and perfluorooctane sulfonamide (PFOSA) between water and sediment.” Chemosphere 85 (5):731-737. https://doi.org/10.1016/j.chemosphere.2011.06.046.

AK DEC. 2009. Site Characterization Work Plan and Reporting Guidance for Investigation of Contaminated Sites.

AK DEC. 2014. Spill Tactics for Alaska Responders. Seldovia, AK. https://dec.alaska.gov/spar/ppr/response-resources/star-manual/.

Al-Amoudi, Ahmed, and Robert W. Lovitt. 2007. “Fouling strategies and the cleaning system of NF membranes and factors affecting cleaning efficiency.” Journal of Membrane Science 303 (1):4-28. https://doi.org/10.1016/j.memsci.2007.06.002.

Al-Amoudi, Ahmed S., and A. Mohammed Farooque. 2005. “Performance restoration and autopsy of NF membranes used in seawater pretreatment.” Desalination 178 (1):261-271. https://doi.org/10.1016/j.desal.2004.11.048.

Al-Niami, A. N. S., and K. R. Rushton. 1977. “Analysis of flow against dispersion in porous media.” Journal of Hydrology 33 (1):87-97. https://doi.org/10.1016/0022-1694(77)90100-7.

Alaska Clean Seas. 2017. Alaska Clean Seas Tactics Manual, Revision 15, June 2021. http://www.alaskacleanseas.org/documents/.

Aleksandrov, Krasimir, Hans-Joachim Gehrmann, Manuela Hauser, Hartmut Mätzing, Daniel Pigeon, Dieter Stapf, and Manuela Wexler. 2019. “Waste incineration of Polytetrafluoroethylene (PTFE) to evaluate potential formation of per- and Poly-Fluorinated Alkyl Substances (PFAS) in flue gas.” Chemosphere 226:898-906. https://doi.org/10.1016/j.chemosphere.2019.03.191.

Alexander, B. H., and G. W. Olsen. 2007. “Bladder cancer in perfluorooctanesulfonyl fluoride manufacturing workers.” Ann Epidemiol 17 (6):471-8. https://doi.org/10.1016/j.annepidem.2007.01.036.

Alexander, B. H., G. W. Olsen, J. M. Burris, J. H. Mandel, and J. S. Mandel. 2003. “Mortality of employees of a perfluorooctanesulphonyl fluoride manufacturing facility.” Occup Environ Med 60 (10):722-9. http://doi.org/10.1136/oem.60.10.722.

Alexandrescu, F., E. Rizzo, L. Pizzol, and A. Critto. 2015. “Building a network-based expert-stakeholder framework for sustainable regeneration.” AquaConSoil Conference 2015, Copenhagen, Denmark, June 9-12 http://www.aquaconsoil.org.

Alfa Aesar. “Alfa Aesar web page.” https://www.alfa.com/en/catalog/category/chemicals/.

Allred, B. McKay, Johnsie R. Lang, Morton A. Barlaz, and Jennifer A. Field. 2014. “Orthogonal zirconium diol/C18 liquid chromatography–tandem mass spectrometry analysis of poly and perfluoroalkyl substances in landfill leachate.” Journal of Chromatography A 1359:202-211. https://doi.org/10.1016/j.chroma.2014.07.056.

Allred, B. McKay, Johnsie R. Lang, Morton A. Barlaz, and Jennifer A. Field. 2015. “Physical and Biological Release of Poly- and Perfluoroalkyl Substances (PFASs) from Municipal Solid Waste in Anaerobic Model Landfill Reactors.” Environmental Science & Technology 49 (13):7648-7656. https://doi.org/10.1021/acs.est.5b01040.

Altarawneh, Mohammednoor, Mansour H. Almatarneh, and Bogdan Z. Dlugogorski. 2022. “Thermal decomposition of perfluorinated carboxylic acids: Kinetic model and theoretical requirements for PFAS incineration.” Chemosphere 286:131685. https://doi.org/10.1016/j.chemosphere.2021.131685.

Alvarez, David A. 2010. Guidelines for the use of the semipermeable membrane device (SPMD) and the polar organic chemical integrative sampler (POCIS) in environmental monitoring studies. Techniques and Methods 1-D4, in Collection of Water Data by Direct Measurement. Reston, VA: U.S. Geological Survey.

Alvarez, David A., Steven R. Corsi, Laura A. De Cicco, Daniel L. Villeneuve, and Austin K. Baldwin. 2021. “Identifying Chemicals and Mixtures of Potential Biological Concern Detected in Passive Samplers from Great Lakes Tributaries Using High-Throughput Data and Biological Pathways.” Environmental Toxicology and Chemistry 40 (8):2165-2182. https://doi.org/10.1002/etc.5118.

Amec Foster Wheeler. 2017. Site 8 Pilot Test Results Report, Former Pease Air Force Base. Texas Prepared for Air Force Civil Engineering Center. Joint Base San Antonio – Lakeland.

Amerex Corporation. 2006. Material Safety Data Sheet, AFFF Foam Concentrate. https://www.amerex-fire.com/learning-center/data-sheets/.

American Cancer Society. 2016. Teflon and Perfluorooctanoic Acid (PFOA). https://www.cancer.org/cancer/cancer-causes/teflon-and-perfluorooctanoic-acid-pfoa.html.

American Chemistry Council. 2021. “Alliance for Telomer Chemistry Stewardship (ATCS).” accessed 2021. https://www.americanchemistry.com/industry-groups/alliance-for-telomer-chemistry-stewardship-atcs.

Amini, Adib, Youngwoon Kim, Jie Zhang, Treavor Boyer, and Qiong Zhang. 2015. “Environmental and economic sustainability of ion exchange drinking water treatment for organics removal.” Journal of Cleaner Production 104:413-421. https://doi.org/10.1016/j.jclepro.2015.05.056.

Amraoui, Imen, Noureddine Khalloufi, and Samir Touaylia. 2018. “Effects to perfluorooctane sulfonate (PFOS) on the mollusk Unio ravoisieri under laboratory exposure.” Chemistry and Ecology 34 (4):324-339. 10.1080/02757540.2018.1433168.

An, Youn-Joo, and Elizabeth R. Carraway. 2002. “PAH degradation by UV/H2O2 in perfluorinated surfactant solutions.” Water Research 36 (1):309-314. https://doi.org/10.1016/S0043-1354(01)00206-8.

Anderson, J. K., R. W. Brecher, I. T. Cousins, J. DeWitt, H. Fiedler, K. Kannan, C. R. Kirman, J. Lipscomb, B. Priestly, R. Schoeny, J. Seed, M. Verner, and S. M. Hays. 2022. “Grouping of PFAS for human health risk assessment: Findings from an independent panel of experts.” Regulatory Toxicology and Pharmacology 134:105226. https://doi.org/10.1016/j.yrtph.2022.105226.

Anderson, Richard H. 2021. “The Case for Direct Measures of Soil-to-Groundwater Contaminant Mass Discharge at AFFF-Impacted Sites.” Environmental Science & Technology 55 (10):6580-6583. https://doi.org/10.1021/acs.est.1c01543.

Anderson, R. Hunter, Dave T. Adamson, and Hans F. Stroo. 2019. “Partitioning of poly- and perfluoroalkyl substances from soil to groundwater within aqueous film-forming foam source zones.” Journal of Contaminant Hydrology 220:59-65. https://doi.org/10.1016/j.jconhyd.2018.11.011.

Anderson, Richard H., James B. Feild, Heidi Dieffenbach-Carle, Omneya Elsharnouby, and Rita K. Krebs. 2022.

"Assessment of PFAS in collocated soil and porewater samples at an AFFF-impacted source zone: Field-scale validation of suction lysimeters." Chemosphere 308:136247. https://doi.org/10.1016/j.chemosphere.2022.136247.

Anderson, R. Hunter, G. Cornell Long, Ronald C. Porter, and Janet K. Anderson. 2016. "Occurrence of select perfluoroalkyl substances at U.S. Air Force aqueous film-forming foam release sites other than fire-training areas: Field-validation of critical fate and transport properties." Chemosphere 150:678-685. https://doi.org/10.1016/j.chemosphere.2016.01.014.

Andersson, Eva M., Kristin Scott, YiYi Xu, Ying Li, Daniel S. Olsson, Tony Fletcher, and Kristina Jakobsson. 2019. "High exposure to perfluorinated compounds in drinking water and thyroid disease. A cohort study from Ronneby, Sweden." Environmental Research 176:108540. https://doi.org/10.1016/j.envres.2019.108540.

Andrews, David Q., and Olga V. Naidenko. 2020. "Population-Wide Exposure to Per- and Polyfluoroalkyl Substances from Drinking Water in the United States." Environmental Science & Technology Letters 7 (12):931-936. 10.1021/acs.estlett.0c00713.

Angus Fire. 2015. "Foam Disposal Guide, Managing Firewater Runoff and Accidental Spills."

Angus Fire. 2017. Firefighting Foam Storage Guidance. 6164. https://angusfire.co.uk.

Ankley, Gerald T., Philippa Cureton, Robert A. Hoke, Magali Houde, Anupama Kumar, Jessy Kurias, Roman Lanno, Chris McCarthy, John Newsted, Christopher J. Salice, Bradley E. Sample, Maria S. Sepúlveda, Jeffery Steevens, and Sara Valsecchi. 2020. "Assessing the Ecological Risks of Per- and Polyfluoroalkyl Substances: Current State-of-the Science and a Proposed Path Forward." Environmental Toxicology and Chemistry 40 (3):564-605. https://doi.org/10.1002/etc.4869.

Ankley, G. T., D. W. Kuehl, M. D. Kahl, K. M. Jensen, B. C. Butterworth, and J. W. Nichols. 2004. "Partial life-cycle toxicity and bioconcentration modeling of perfluorooctanesulfonate in the northern leopard frog (Rana pipiens)." Environ Toxicol Chem 23 (11):2745-55.

Annunziato Kate, M., Jeffery Doherty, Jonghwa Lee, M. Clark John, Wenle Liang, W. Clark Christopher, Malina Nguyen, A. Roy Monika, and R. Timme-Laragy Alicia. 2020. "Chemical Characterization of a Legacy Aqueous Film-Forming Foam Sample and Developmental Toxicity in Zebrafish (Danio rerio)." Environmental Health Perspectives 128 (9):097006. https://doi.org/10.1289/EHP6470.

ANSES. 2017. Development of oral-administered treatment for TRV by Perfluorohexanoic acid (PFHxA). Maisons-Alfort, France: Environmental and Occupational Health & Safety French Agency for Food.

Antea Group. 2011. Perfluorocarbon (PFC)-Containing Firefighting foams and their Use in Minnesota: Survey and Sampling Activities, State Fiscal Year 2011. https://www.pca.state.mn.us/sites/default/files/c-pfc1-20.pdf.

Anumol, Tarun, Sonia Dagnino, Darcy R. Vandervort, and Shane A. Snyder. 2016. "Transformation of Polyfluorinated compounds in natural waters by advanced oxidation processes." Chemosphere 144:1780-1787. https://doi.org/10.1016/j.chemosphere.2015.10.070.

Ao, Junjie, Tao Yuan, Hui Xia, Yuning Ma, Zhemin Shen, Rong Shi, Ying Tian, Jun Zhang, Wenjin Ding, Li Gao, Xiaodong Zhao, and Xiaodan Yu. 2019. "Characteristic and human exposure risk assessment of per- and polyfluoroalkyl substances: A study based on indoor dust and drinking water in China." Environmental Pollution 254:112873. https://doi.org/10.1016/j.envpol.2019.07.041.

APHA. 2016. Reducing Human Exposure to Highly Fluorinated Chemicals to Protect Public Health. Policy Number 20163: American Public Health Association. https://www.apha.org/policies-and-advocacy/public-health-policy-statements/policy-database/2016/12/21/reducing-human-exposure-to-highly-fluorinated-chemicals.

API. 2020. Firefighting Foam Transition Guidance. Washington, D.C.: American Petroleum Institute. www.api.org.

Appleman, T., C.P. Higgins, O. Quinones, B. Vanderford, C. Klstad, J. Ziegler-Holady, and E. Dickenson. 2014. "Treatment of Poly- and Perfluoroalkyl Substances in U.S. Full-Scale Water Treatment Systems." Water Research 51:246-255. https://doi.org/10.1016/j.watres.2013.10.067.

Appleman, Timothy D., Eric R. V. Dickenson, Christopher Bellona, and Christopher P. Higgins. 2013. “Nanofiltration and granular activated carbon treatment of perfluoroalkyl acids.” Journal of Hazardous Materials 260:740-746. https://doi.org/10.1016/j.jhazmat.2013.06.033.

Arabi, S. and A. Lugowski. 2015. “Lessons Learned from Successful Applications of Biological Landfill Leachate Treatment.” Environmental Science and Engineering Magazine 28.

Archroma Nuva. 2017. Aerobic Transformation in Soil study conducted under OECD 307. Submitted to U.S. EPA by Archroma U.S. Inc. RP2116 GA 39/13-1: Noack Laboratory GmbH.

Argonne. 2021. Final Derivation of PFAS Ecological Screening Values. Completed under interagency agreement between the U.S. Department of Energy (DOE), Argonne National Laboratory (Argonne), and AFCEC: Argonne National Laboratory Environmental Science Division. www.denix.osd.mil/dodepa/denix-files/sites/85/2022/10/Final-PFAS-ESV-Report_Sept-2021_508.pdf.

Arias Espana, Victor Andres, Megharaj Mallavarapu, and Ravi Naidu. 2015. “Treatment technologies for aqueous perfluorooctanesulfonate (PFOS) and perfluorooctanoate (PFOA): A critical review with an emphasis on field testing.” Environmental Technology & Innovation 4:168-181. https://doi.org/10.1016/j.eti.2015.06.001.

Arias, V. A., R. Naidu, Chadalavada S., and Mallavarapu. M. 2013. “A novel technology for treatment of aqueous fire fighting foams (AFFF) contaminated wastewater.” Cleanup 2013, Melbourne, Australia https://www.crccare.com/events/cleanup-13-5th-international-contaminated-site-remediation-conference.

Armitage, James, Ian T. Cousins, Robert C. Buck, Konstantinos Prevedouros, Mark H. Russell, Matthew MacLeod, and Stephen H. Korzeniowski. 2006. “Modeling Global-Scale Fate and Transport of Perfluorooctanoate Emitted from Direct Sources.” Environmental Science & Technology 40 (22):6969-6975. 10.1021/es0614870.

Armitage, James M., Jon A. Arnot, and Frank Wania. 2012. “Potential Role of Phospholipids in Determining the Internal Tissue Distribution of Perfluoroalkyl Acids in Biota.” Environmental Science & Technology 46 (22):12285-12286. https://doi.org/10.1021/es304430r.

Armitage, James M., Matthew MacLeod, and Ian T. Cousins. 2009. “Modeling the Global Fate and Transport of Perfluorooctanoic Acid (PFOA) and Perfluorooctanoate (PFO) Emitted from Direct Sources Using a Multispecies Mass Balance Model.” Environmental Science & Technology 43 (4):1134-1140. 10.1021/es802900n.

Armitage, J. M., U. Schenker, M. Scheringer, J. W. Martin, M. Macleod, and I. T. Cousins. 2009. “Modeling the Global Fate and Transport of Perfluorooctane Sulfonate (PFOS) and Precursor Compounds in Relation to Temporal Trends in Wildlife Exposure.” Environmental Science & Technology 43. http://doi.org/10.1021/Es901448p.

Aro, Rudolf, Ulrika Eriksson, Anna Kärrman, Fangfang Chen, Thanh Wang, and Leo W. Y. Yeung. 2021. “Fluorine Mass Balance Analysis of Effluent and Sludge from Nordic Countries.” ACS ES&T Water 1 (9):2087-2096. 10.1021/acsestwater.1c00168.

Arp, Hans Peter H., and Kai-Uwe Goss. 2009. “Irreversible sorption of trace concentrations of perfluorocarboxylic acids to fiber filters used for air sampling.” Atmospheric Environment 43:3654-3655. https://doi.org/10.1016/j.atmosenv.2009.03.001.

Arp, H. P. H., C. Niederer, and K.-U. Goss. 2006. “Predicting the Partitioning Behavior of Various Highly Fluorinated Compounds.” Environmental Science & Technology 40 (23):7298-7304. https://doi.org/10.1021/es060744y.

Arrieta-Cortes, R., P. Farias, C. Hoyo-Vadillo, and M. Kleiche-Dray. 2017. “Carcinogenic risk of emerging persistent organic pollutant perfluorooctane sulfonate (PFOS): A proposal of classification.” Regul Toxicol Pharmacol 83:66-80. 10.1016/j.yrtph.2016.11.021.

Arvaniti, O. S., Y. Hwang, H. R. Andersen, T. S. Nikolaos, and S. S. Athanasios. 2014. “Removal of Perfluorinated Compounds from Water using Nanoscale Zero-Valent Iron.” Singapore International Water Week.

Arvaniti, Olga S., Yuhoon Hwang, Henrik R. Andersen, Athanasios S. Stasinakis, Nikolaos S. Thomaidis, and Maria Aloupi. 2015. “Reductive degradation of perfluorinated compounds in water using Mg-aminoclay coated nanoscale zero valent iron.” Chemical Engineering Journal 262:133-139. https://doi.org/10.1016/j.cej.2014.09.079.

Arvaniti, O.S., and A.S. Stasinakis. 2015. “Review on the occurrence, fate and removal of perfluorinated compounds during wastewater treatment.” Science of the Total Environment 524-525:81-92. https://doi.org/10.1016/j.scitotenv.2015.04.023.

Asher, Brian J., Yuan Wang, Amila O. De Silva, Sean Backus, Derek C. G. Muir, Charles S. Wong, and Jonathan W. Martin. 2012. “Enantiospecific Perfluorooctane Sulfonate (PFOS) Analysis Reveals Evidence for the Source Contribution of PFOS-Precursors to the Lake Ontario Foodweb.” Environmental Science & Technology 46 (14):7653-7660. https://doi.org/10.1021/es301160r.

ASTM. 2007. Standard Guide for Sampling Ground-Water Monitoring Wells. https://www.astm.org/.

ASTM. 2011. Standard Practice for Environmental Site Assessments: Phase II Environmental Site Assessment Process. West Conshocken, PA: ASTM International https://www.astm.org/.

ASTM. 2013. Standard Guide for Sampling Ground-Water Monitoring Wells. West Conshocken, PA: ASTM International https://www.astm.org/.

ASTM. 2013. Standard Guide for Selection of Soil and Rock Sampling Devices Used with Drill Rigs for Environmental Investigations. West Conshocken, PA: ASTM International .

ASTM. 2013. Standard Practice for Environmental Site Assessments: Phase I Environmental Site Assessment Process. West Conshocken, PA: ASTM International https://www.astm.org/.

ASTM. 2013. Standard Guide for Conducting Bioconcentration Tests with Fishes and Saltwater Bivalve Mollusks. West Conshocken, PA: ASTM International https://www.astm.org/.

ASTM. 2014. Standard Guide for Core Sampling Submerged, Unconsolidated Sediments. West Conshocken, PA: ASTM International https://www.astm.org/.

ASTM. 2014. Standard Guide for Developing Conceptual Site Models for Contaminated Sites. West Conshocken, PA: ASTM International https://www.astm.org/.

ASTM. 2015. Standard Guide for Risk Based Corrective Action. E2081-00(2015). West Conshohocken, PA: ASTM International. https://www.astm.org/.

ASTM. 2016. Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials using A Flexible Wall Permeameter. D5084-16a. West Conshohocken, PA. https://www.astm.org/.

ASTM. 2017. Standard Test Method for Determination of Perfluorinated Compounds in Soil by Liquid Chromatography Tandem Mass Spectrometry (LC/MS/MS). West Conshocken, PA: ASTM International https://www.astm.org/.

ASTM. 2017. Standard Test Method for Determination of Perfluorinated Compounds in Water, Sludge, Influent, Effluent and Wastewater by Liquid Chromatography Tandem Mass Spectrometry (LC/MS/MS). West Conshocken, PA: ASTM International https://www.astm.org/.

ASTM. 2018. Standard Guide for Pore-Liquid Sampling from the Vadose Zone. D4696-18. West Conshocken, PA. https://www.astm.org.

ASTM. 2021. Standard Guide for Management of Investigation-Derived Waste Associated with PFAS. E3274-21. West Conshohocken, PA: ASTM International. https://www.astm.org.

ASTM 2022. Standard Method for Determination of Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous Matrices by Co-solvation followed by Liquid Chromatography Tandem Mass Spectrometry (LC/MS/MS). D8421-22. West Conshohocken, PA. https://www.astm.org.

ASTSWMO. 2015. Perfluorinated Chemicals (PFCs): Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonate (PFOS) Information Paper. Washington, D. C.: Remediation and Reuse Focus Group. Federal Facilities Research Center. https://clu-in.org/download/contaminantfocus/pops/POPs-ASTSWMO-PFCs-2015.pdf.

Ateia, Mohamed, Md Arifuzzaman, Steven Pellizzeri, Mohamed F. Attia, Nishanth Tharayil, Jeffrey N. Anker, and Tanju Karanfil. 2019. “Cationic polymer for selective removal of GenX and short-chain PFAS from surface waters and wastewaters at ng/L levels." Water Research 163:114874. https://doi.org/10.1016/j.watres.2019.114874.

Ateia, Mohamed, Dora Chiang, Michaela Cashman, and Carolyn Acheson. 2023. "Total Oxidizable Precursor (TOP) Assay─Best Practices, Capabilities and Limitations for PFAS Site Investigation and Remediation." Environmental Science & Technology Letters. 10.1021/acs.estlett.3c00061.

Atkinson, C., S. Blake, T. Hall, R. Kanda, and P. Rumsby. 2008. Survey of the prevalence of perfluorooctane sulphonate (PFOS), perfluorooctanoic acid (PFOA) and related compounds in drinking water and their sources. http://dwi.defra.gov.uk/research/completedresearch/reports/DWI70_2_212PFOS.pdf.

ATSDR. 2008. Health Consultation: PFOS Detections in the City of Brainerd, Minnesota – City of Brainerd, Crow Wing County, Minnesota.

ATSDR. 2011. Principles of Community Engagement, Second Edition. NIH Publication No. 11-7782: CTSA Community Engagement Key Function Committee Task Force.

ATSDR. 2012. Public Health Assessment for Perfluorochemical Contamination in Southern Washington County, Northern Dakota County, and Southeastern Ramsey County, Minnesota.

ATSDR. 2013. Health Consultation. Exposure Investigation Report. Perfluorochemical serum sampling in the vicinity of Decatur, Alabama. Morgan, Lawrence, and Limestone Counties. http://www.atsdr.cdc.gov/HAC/pha/Decatur/Perfluorochemical_Serum%20Sampling.pdf

ATSDR. 2016. "Per- and Polyfluoroalkyl Substances and Your Health: Health Effects of PFAS." ATSDR. https://www.atsdr.cdc.gov/pfc/health_effects_pfcs.html.

ATSDR. 2017. An Overview of Perfluoroalkyl and Polyfluoroalkyl Substances and Interim Guidance for Clinicians Responding to Patient Exposure Concerns. https://www.atsdr.cdc.gov/pfc/docs/pfas_clinician_fact_sheet_508.pdf.

ATSDR. 2018. Toxicological profile for Perfluoroalkyls (Draft for Public Comment). U.S. Department of Health and Human Services. https://www.atsdr.cdc.gov/ToxProfiles/tp200.pdf.

ATSDR. 2018. "Per- and Polyfluoroalkyl Substances (PFAS) and Your Health. Understanding PFAS Exposure." https://www.atsdr.cdc.gov/pfas/understanding-PFAS-exposure.html.

ATSDR. 2018. "Per- and Polyfluoroalkyl Substances (PFAS) and Your Health." Accessed September 2018. https://www.atsdr.cdc.gov/pfas/index.html.

ATSDR. 2018. "Toxic Substances Portal. Minimal Risk Levels (MRLs) for Professionals." accessed 2023. https://www.atsdr.cdc.gov/mrls/.

ATSDR. 2018. ToxGuide for Perfluoroalkyls. Atlanta, GA. https://www.atsdr.cdc.gov/toxguides/toxguide-200.pdf.

ATSDR. 2018. Human Health Toxicity Values for Hexafluoropropylene Oxide (HFPO) Dimer Acid and Its Ammonium Salt (CASRN 13252-13-6 and CASRN 62037-80-3). Also Known as "GenX Chemicals". EPA-823-P-18-001. Washington D.C.: Office of Water U.S Environmental Protection Agency. https://www.epa.gov/pfas/genx-toxicity-assessments-documents.

ATSDR. 2018. Framework for Assessing Health Impacts of Multiple Chemicals and Other Stressors (Update). Atlanta, GA: U.S. Department of Health and Human Services Agency for Toxic Substances and Disease Registry, Public Health Service.

ATSDR. 2019. Health Consultation PFAS HC-508. EPA PWS ID: 1951020. https://www.atsdr.cdc.gov/HAC/pha/pease/Pease-Tradeport-Public-Water-PFAS-HC-508.pdf.

ATSDR. 2019. "Per- and Polyfluoroalkyl Substances (PFAS) and Your Health." Last Modified June 24, 2020. accessed 2020. https://www.atsdr.cdc.gov/pfas/pfas-exposure.html.

ATSDR. 2020. "PFAS in the U.S. Population." Last Modified June 24, 2020. accessed 2020. https://www.atsdr.cdc.gov/pfas/health-effects/us-population.html.

ATSDR. 2020. “Multi-site Health Study – PFAS Cooperative Agreement.” Last Modified July 22, 2020. accessed 2020. https://www.atsdr.cdc.gov/pfas/activities/studies/multi-site.html.

ATSDR. 2020. ToxGuide for Perfluoroalkyls. Atlanta, GA: U.S. Department of Health and Human Services. https://www.atsdr.cdc.gov/toxguides/toxguide-200.pdf.

ATSDR. 2020. Health Consultation: Per- and Polyfluoroalkyl Substances (PFAS) in the Pease Tradeport Public Water System. EPA PWS ID: 1951020; Pease Air Force Base; Portsmouth, Newington, and Greenland, New Hampshire. EPA Facility ID: NH7570024847. Atlanta, GA: U.S. Department of Health and Human Services Agency for Toxic Substances and Disease Registry, Public Health Service.

ATSDR. 2021. Toxicological Profile for Perfluoroalkyls. Atlanta, GA: U.S. Department of Health and Human Services. https://www.atsdr.cdc.gov/ToxProfiles/tp200.pdf.

ATSDR. 2022. Final Report: Findings Across Ten Exposure Assessment (EA) Sites. Atlanta, GA: U.S. Department of Health and Human Services. https://www.atsdr.cdc.gov/pfas/activities/assessments/final-report.html.

ATSDR. 2022. Health Consultation: Evaluation of per-and polyfluoroalkyl substances (PFAS) detected in private residential drinking water wells located within 1 mile of the Pease International Tradeport, Pease Air Force Base, EPA Facility ID: NH7570024847. Atlanta, GA: U.S. Department of Health and Human Services. https://www.atsdr.cdc.gov/HAC/pha/pease/PeaseAFB-HC-508.pdf.

ATSDR. 2022. PFAS Multi-site Study. https://www.atsdr.cdc.gov/pfas/activities/studies/multi-site.html.

ATSDR. 2023. “PFAS Blood Level Estimation Tool.” Last Modified March 13, 2023. accessed 2023. https://www.atsdr.cdc.gov/pfas/bloodlevelestimator/index.html.

Australia Government DOD. 2007. Environmental Guidelines for Management of Fire Fighting Aqueous Film Forming Foam (AFFF) Products. Directorate of Environmental Impact Management.

Australia Government DOD. 2021. Defence PFAS Construction and Maintenance Framework. Version 3.0. https://defence.gov.au/EstateManagement/governance/policy/environment/PFAS/docs/DefencePFASConstructionandMaintenanceFramework.pdf.

Australia Government DOH. 2018. PFAS Expert Health Panel – Report to the Minister. https://www1.health.gov.au/internet/main/publishing.nsf/Content/C9734ED6BE238EC0CA2581BD00052C03/$File/expert-panel-report.pdf.

Australian Government DoEE. 2016. Commonwealth Environmental Management Guidance on Perfluorooctane Sulfonic Acid (PFOS) and Perfluorooctanoic Acid (PFOA) (Draft). Department of the Environment and Energy. https://www.awe.gov.au/sites/default/files/env/pages/dfb876c5-581e-48b7-868c-242fe69dad68/files/draft-environmental-mgt-guidance-pfos-pfoa.pdf.

Avsec, R. 2015. “Seven steps to cleaner firefighter PPE.”. https://www.firerescue1.com/fire-products/turnoutgear/articles/3218580-7-steps-to-cleaner-firefighter-PPE/.

Awad, Emily, Xianming Zhang, Satyendra P. Bhavsar, Steve Petro, Patrick W. Crozier, Eric J. Reiner, Rachael Fletcher, Sheryl A. Tittlemier, and Eric Braekevelt. 2011. “Long-Term Environmental Fate of Perfluorinated Compounds after Accidental Release at Toronto Airport.” Environmental Science & Technology 45 (19):8081-8089. 10.1021/es2001985.

Awad, Raed, Yihui Zhou, Elisabeth Nyberg, Shahla Namazkar, Wu Yongning, Qianfen Xiao, Yaije Sun, Zhiliang Zhu, Åke Bergman, and Jonathan P. Benskin. 2020. “Emerging per- and polyfluoroalkyl substances (PFAS) in human milk from Sweden and China.” Environmental Science: Processes & Impacts 22 (10):2023-2030. http://dx.doi.org/10.1039/D0EM00077A.

AWWA. 2016. Perfluorinated Compounds Treatment and Removal.

AWWA. 2019. Per- and Polyfluoroalkyl Substances (PFAS) Treatment. Denver, CO: American Water Works Association. https://www.awwa.org/Portals/0/AWWA/ETS/Resources/Per-andPolyfluoroalkylSubstances(PFAS)-Treatment.pdf?ver=

2019-08-14-090249-580.

Babut, M., P. Labadie, C. Simonnet-Laprade, G. Munoz, M.-C. Roger, B. J. D. Ferrari, H. Budzinski, and E. Sivade. 2017. “Per- and poly-fluoroalkyl compounds in freshwater fish from the Rhône River: Influence of fish size, diet, prey contamination and biotransformation.” Science of The Total Environment 605-606:38-47.

Bach, C. C., B. H. Bech, N. Brix, E. A. Nohr, J. P. Bonde, and T. B. Henriksen. 2015. “Perfluoroalkyl and polyfluoroalkyl substances and human fetal growth: a systematic review.” Crit Rev Toxicol 45 (1):53-67. 10.3109/10408444.2014.952400.

Backe, Will J., Thomas C. Day, and Jennifer A. Field. 2013. “Zwitterionic, Cationic, and Anionic Fluorinated Chemicals in Aqueous Film Forming Foam Formulations and Groundwater from U.S. Military Bases by Nonaqueous Large-Volume Injection HPLC-MS/MS.” Environmental Science & Technology 47 (10):5226-5234. 10.1021/es3034999.

Badruddoza, A.Z.M., B. Bhattarai, and R.P Suri. 2017. “Environmentally Friendly Cyclodextrin-Ionic Liquid Polyurethane-Modified Magnetic Sorbent for the Removal of PFOA.” ACS Sustainable Chemistry & Engineering 5.

Baduel, C., C. J. Paxman, and J. F. Mueller. 2015. “Perfluoroalkyl substances in a firefighting training ground (FTG), distribution and potential future release.” Journal of Hazardous Materials 296:46-53. https://doi.org/10.1016/j.jhazmat.2015.03.007.

Baerlocher, C., L.B. McCusker, and D.H. Olson 2007. “Atlas of zeolite framework types.”.

Bai, Xuelian, and Yeongkwon Son. 2021. “Perfluoroalkyl substances (PFAS) in surface water and sediments from two urban watersheds in Nevada, USA.” Science of The Total Environment 751:141622. https://doi.org/10.1016/j.scitotenv.2020.141622.

Baker, Joel E., and Steven J. Eisenreich. 1990. “Concentrations and fluxes of polycyclic aromatic hydrocarbons and polychlorinated biphenyls across the air-water interface of Lake Superior.” Environmental Science & Technology 24 (3):342-352. 10.1021/es00073a009.

Bakke, Torgeir, Torsten Källqvist, Anders Ruus, Gijs Breedveld, and Ketil Hylland. 2010. “Development of sediment quality criteria in Norway.” 10:172-178. https://doi.org/10.1007/s11368-009-0173-y.

Bălan Simona, Andreea, Chander Mathrani Vivek, Fengmao Guo Dennis, and Maurice Algazi André. “Regulating PFAS as a Chemical Class under the California Safer Consumer Products Program.” Environmental Health Perspectives 129 (2):025001. 10.1289/EHP7431.

Balbi, Teresa, Caterina Ciacci, Elena Grasselli, Arianna Smerilli, Adriana Voci, and Laura Canesi. 2017. “Utilization of Mytilus digestive gland cells for the in vitro screening of potential metabolic disruptors in aquatic invertebrates.” Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology 191:26-35. https://doi.org/10.1016/j.cbpc.2016.08.009.

Balgooyen, Sarah, and Christina K. Remucal. 2022. “Tributary Loading and Sediment Desorption as Sources of PFAS to Receiving Waters.” ACS ES&T Water 2 (3):436-445. 10.1021/acsestwater.1c00348.

Ballesteros, V., O. Costa, C. Iniguez, T. Fletcher, F. Ballester, and M. J. Lopez-Espinosa. 2017. “Exposure to perfluoroalkyl substances and thyroid function in pregnant women and children: A systematic review of epidemiologic studies.” Environ Int 99:15-28. 10.1016/j.envint.2016.10.015.

Bamdad, Hanieh, Sadegh Papari, Emma Moreside, and Franco Berruti. 2022. High-Temperature Pyrolysis for Elimination of Per- and Polyfluoroalkyl Substances (PFAS) from Biosolids. Processes 10 (11). 10.3390/pr10112187.

Bangma, Jacqueline T., John A. Bowden, Arnold M. Brunell, Ian Christie, Brendan Finnell, Matthew P. Guillette, Martin Jones, Russell H. Lowers, Thomas R. Rainwater, Jessica L. Reiner, Philip M. Wilkinson, and Louis J. Guillette Jr. 2017. “Perfluorinated alkyl acids in plasma of American alligators (Alligator mississippiensis) from Florida and South Carolina.” Environmental Toxicology and Chemistry 36 (4):917-925. 10.1002/etc.3600.

Banks, R. E., B. E. Smart, and J.C. Tatlow, eds. 1994. Organofluorine Chemistry: Principles and Commercial Applications, Spring Science + Business Media. New York: Springer. ISBN No. 978-1-4899-1202-2.

Banzhaf, Stefan, Marko Filipovic, Jeffrey Lewis, Charlotte J. Sparrenbom, and Roland Barthel. 2017. “A review of contamination of surface-, ground-, and drinking water in Sweden by perfluoroalkyl and polyfluoroalkyl substances (PFASs).” Ambio 46 (3):335-346. https://doi.org/10.1007/s13280-016-0848-8.

Bao, Yixiang, Jun Huang, Giovanni Cagnetta, and Gang Yu. 2019. “Removal of F–53B as PFOS alternative in chrome plating wastewater by UV/Sulfite reduction.” Water Research 163:114907. https://doi.org/10.1016/j.watres.2019.114907.

Bao, Y., J. Niu, Z. Xu, D. Gao, J. Shi, X. Sun, and Q. Huang. 2014. “Removal of perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) from water by coagulation: mechanisms and 11029 influencing factors.” Journal of Colloid and Interface Science 434. 10.1016/j.jcis.2014.07.041.

Barber, Jonathan L., Urs Berger, Chakra Chaemfa, Sandra Huber, Annika Jahnke, Christian Temme, and Kevin C. Jones. 2007. “Analysis of per- and polyfluorinated alkyl substances in air samples from Northwest Europe.” Journal of Environmental Monitoring 9 (6):530-541. 10.1039/B701417A.

Barclift. 2013. “Navy Case Study: Occurrence of Two Emerging Contaminants (PFOA & PFOS) at former NAS South Weymouth, MA.” Federal Remediation Technology Roundtable Fall.

Bardos, R. Paul, Brian D. Bone, Richard Boyle, Frank Evans, Nicola D. Harries, Trevor Howard, and Jonathan W. N. Smith. 2016. “The rationale for simple approaches for sustainability assessment and management in contaminated land practice.” Science of The Total Environment 563-564:755-768. https://doi.org/10.1016/j.scitotenv.2015.12.001.

Barisci, S., and S. Rominder. 2021. “Occurrence and removal of poly/perfluoroalkyl substances (PFAS) in municipal and industrial wastewater treatment plants.” Water Science & Technology 84 (12):3442-3468. https://doi.org/10.2166/wst.2021.484.

Barmentlo, S. H., J. M. Stel, M. van Doorn, C. Eschauzier, P. de Voogt, and M. H. Kraak. 2015. “Acute and chronic toxicity of short chained perfluoroalkyl substances to Daphnia magna.” Environ Pollut 198:47-53. 10.1016/j.envpol.2014.12.025.

Barr. 2017. DRAFT Conceptual Modeling of PFOA Fate and Transport: North Bennington, VT. Minneapolis, MN. https://anrweb.vt.gov/PubDocs/DEC/PFOA/Consent%20Order%20and%20Technical%20Documents/Core%20Technical%20Documents/Conceptual%20Site%20Model/Saint-Gobain%20VT%20Draft%20CSM%20June2017%20Main%20Report.pdf.

Barr Engineering. 2022. Results of the August 24-25, 2022 Regenerative Thermal Oxidizer Compliance Tests at Saint-Gobain Performance Plastics in Merrimack, New Hampshire. https://www4.des.state.nh.us/OneStopPub/Air/330110016522-0048TypeSTReport.pdf.

Bartell, S. M. 2017. “Online Serum PFOA Calculator for Adults.” Environ Health Perspect 125 (10):104502. 10.1289/ehp2820.

Bartell, S. M., A. M. Calafat, C. Lyu, K. Kato, P. B. Ryan, and K. Steenland. 2010. “Rate of decline in serum PFOA concentrations after granular activated carbon filtration at two public water systems in Ohio and West Virginia.” Environ Health Perspect 118 (2):222-8. 10.1289/ehp.0901252.

Bartlett, Samuel A., and Katherine L. Davis. 2018. “Evaluating PFAS cross contamination issues.” Remediation Journal 28 (2):53-57. 10.1002/rem.21549.

Barton, C. A., M. A. Kaiser, and M. H. Russell. 2010. ” A site-specific screening comparison of modeled and monitored air dispersion and deposition for perfluorooctanoate.” Journal of the Air and Waste Management Association 60.

Barton, Catherine A., Miguel A. Botelho, and Mary A. Kaiser. 2008. “Solid Vapor Pressure and Enthalpy of Sublimation for Perfluorooctanoic Acid.” Journal of Chemical & Engineering Data 53 (4):939-941. 10.1021/je700593d.

Barton, Catherine A., Miguel A. Botelho, and Mary A. Kaiser. 2009. “Solid Vapor Pressure and Enthalpy of Sublimation for Ammonium Perfluorooctanoate.” Journal of Chemical & Engineering Data 54 (3):752-755. 10.1021/je800418m.

Barton, C. A., L. E. Butler, C. J. Zarzecki, J. Flaherty, and M. Kaiser. 2006. “Characterizing perfluorooctanoate in ambient air near the fence line of a manufacturing facility: comparing modeled and monitored values." Journal of the Air and Waste Management Association 56 (1):48-55. 10.1080/10473289.2006.10464429.

Barton, C. A., M. A. Kaiser, and M. H. Russell. 2007. "Partitioning and removal of perfluorooctanoate during rain events: the importance of physical-chemical properties." Journal of Environmental Monitoring 9 (8):839-46. https://doi.org/10.1039/b703510a.

Barzen-Hanson, K. A., S. E. Davis, M. Kleber, and J. A. Field. 2017. "Sorption of Fluorotelomer Sulfonates, Fluorotelomer Sulfonamido Betaines, and a Fluorotelomer Sulfonamido Amine in National Foam Aqueous Film-Forming Foam to Soil." Environmental Science and Technology 51 (21):12394-12404. https://doi.org/10.1021/acs.est.7b03452.

Barzen-Hanson, Krista A., Simon C. Roberts, Sarah Choyke, Karl Oetjen, Alan McAlees, Nicole Riddell, Robert McCrindle, P. Lee Ferguson, Christopher P. Higgins, and Jennifer A. Field. 2017. "Discovery of 40 Classes of Per- and Polyfluoroalkyl Substances in Historical Aqueous Film-Forming Foams (AFFFs) and AFFF-Impacted Groundwater." Environmental Science & Technology 51 (4):2047-2057. 10.1021/acs.est.6b05843.

Battelle. 2018. Current State of the Science for Quantitative Methods to Collect Foam Samples from Water and Solids. Prepared for US EPA Office of Research and Development.

Battelle. 2020. "Understanding the Signature of PFAS – Source Discrimination and Delineation of AFFF and Non-AFFF using HRMS Analysis." accessed 2020. https://www.battelle.org/government-offerings/energy-environment/environmental-services/pfas-assessment-mitigation/pfas-signature-chemical-forensics.

Battelle. 2021. "FAST PFAS Sensor: Forever-Chemicals Finder (Battelle Number 31421-E | N/A)." accessed 2021. https://www.pnnl.gov/available-technologies/fast-pfas-sensor-forever-chemicals-finder.

Baudequin, Clément, Estelle Couallier, Mohammed Rakib, Isabelle Deguerry, Romain Severac, and Martial Pabon. 2011. "Purification of firefighting water containing a fluorinated surfactant by reverse osmosis coupled to electrocoagulation–filtration." Separation and Purification Technology 76 (3):275-282. https://doi.org/10.1016/j.seppur.2010.10.016.

Beach, S. A., J. L. Newsted, K. Coady, and J. P. Giesy. 2006. "Ecotoxicological evaluation of perfluorooctanesulfonate (PFOS)." Rev Environ Contam Toxicol 186:133-74.

Beahm, C., and J. Marts. 2019. 2018 Results for Per- and Polyfluoroalkyl Substances (PFAS) Analyses Performed by USEPA's Office of Research and Development for Samples Collected in Southern New Hampshire. Concord, NH: New Hampshire DES. https://www4.des.state.nh.us/OneStopPub/Air/330110016504192019TypeCR.pdf.

Bečanová, Jitka, Lisa Melymuk, Šimon Vojta, Klára Komprdová, and Jana Klánová. 2016. "Screening for perfluoroalkyl acids in consumer products, building materials and wastes." Chemosphere 164:322-329. https://doi.org/10.1016/j.chemosphere.2016.08.112.

Becanova, Jitka, Zachary S. S. L. Saleeba, Aidan Stone, Anna R. Robuck, Robert H. Hurt, and Rainer Lohmann. 2021. "A graphene-based hydrogel monolith with tailored surface chemistry for PFAS passive sampling." Environmental Science: Nano 8 (10):2894-2907. 10.1039/D1EN00517K.

Becker, Anna Maria, Silke Gerstmann, and Hartmut Frank. 2008. "Perfluorooctane surfactants in waste waters, the major source of river pollution." Chemosphere 72 (1):115-121. https://doi.org/10.1016/j.chemosphere.2008.01.009.

Becker, Anna Maria, Silke Gerstmann, and Hartmut Frank. 2010. "Perfluorooctanoic acid and perfluorooctane sulfonate in two fish species collected from the Roter Main River, Bayreuth, Germany." Bulletin of Environmental Contamination and Toxicology 84 (1):132.

Becker, Joanna M., Tim Parkin, Cindy H. Nakatsu, Jayson D. Wilbur, and Allan Konopka. 2006. "Bacterial Activity, Community Structure, and Centimeter-Scale Spatial Heterogeneity in Contaminated Soil." Microbial Ecology 51 (2):220-231. 10.1007/s00248-005-0002-9.

Becker, S. 2022. "Soil Washing of PFAS-Contaminated Soils." REMTECH East Symposium.

Beesoon, S., S.J. Genuis, J.P. Benskin, and J.W. Martin. 2012. “Exceptionally High Serum Concentrations of Perfluorohexanesulfonate in a Canadian Family are Linked to Home Carpet Treatment Applications.” Environmental Science and Technology 46 (23):12960-12967. https://doi.org/10.1021/es3034654.

Beesoon, S., G. M. Webster, M. Shoeib, T. Harner, J. P. Benskin, and J. W. Martin. 2011. “Isomer profiles of perfluorochemicals in matched maternal, cord, and house dust samples: manufacturing sources and transplacental transfer.” Environ Health Perspect 119 (11):1659-64. 10.1289/ehp.1003265.

Begley, T. H., W. Hsu, G. Noonan, and G. Diachenko. 2008. “Migration of fluorochemical paper additives from food-contact paper into foods and food simulants.” Food Additives & Contaminants: Part A 25 (3):384-390. 10.1080/02652030701513784.

Benotti, Mark J., Loretta A. Fernandez, Graham F. Peaslee, Gregory S. Douglas, Allen D. Uhler, and Stephen Emsbo-Mattingly. 2020. “A forensic approach for distinguishing PFAS materials.” Environmental Forensics 21 (3-4):319-333. 10.1080/15275922.2020.1771631.

Benskin, J. P., V. Phillips, V.L. St. Louis and J.W. Martin. 2011. “Source elucidation of perfluorinated carboxylic acids in remote alpine lake sediment cores.” Environ. Sci. Technol 45 (17):7188-7194. https://doi.org/10.1021/es2011176.

Benskin, J. P., L. Ahrens, D.C.G. Muir, B. F. Scott, C. Spencer, B. Rosenberg, G. Tomy, H. Kylin, Lohmann R., and Martin. J. W. 2011. “Manufacturing Origin of Perfluorooctanoate (PFOA) in Atlantic and Canadian Arctic Seawater.” Environmental Science and Technology 46:677.

Benskin, Jonathan P., Mahmoud Bataineh, and Jonathan W. Martin. 2007. “Simultaneous Characterization of Perfluoroalkyl Carboxylate, Sulfonate, and Sulfonamide Isomers by Liquid Chromatography−Tandem Mass Spectrometry.” Analytical Chemistry 79 (17):6455-6464. 10.1021/ac070802d.

Benskin, J.P., A. O. DeSilva, and J. W. Martin. 2010. “Isomer Profiling of Perfluorinated Substances as a Tool for Source Tracking: A Review of Early Findings and Future Applications.” Reviews of Environmental Contamination and Toxicology 208:111.

Benskin, Jonathan P., Belinda Li, Michael G. Ikonomou, John R. Grace, and Loretta Y. Li. 2012. “Per- and Polyfluoroalkyl Substances in Landfill Leachate: Patterns, Time Trends, and Sources.” Environmental Science & Technology 46 (21):11532-11540. https://doi.org/10.1021/es302471n.

Benskin, J. P., D.C. Muir, B.F. Scott, C. Spencer, A. O. DeSilva, H. Kylin, J. W. Martin, A. Morris, R. Lohmann, G. Tomy, B. Rosenberg, S. Taniyasu, and N. Yamashita. 2012. “Perfluoroalkyl acids in the Atlantic and Canadian Arctic Oceans.” Environmental Science and Technology 46 (11):5815-5823. https://doi.org/10.1021/es300578x.

Bentel, Michael J., Yaochun Yu, Lihua Xu, Zhong Li, Bryan M. Wong, Yujie Men, and Jinyong Liu. 2019. “Defluorination of Per- and Polyfluoroalkyl Substances (PFASs) with Hydrated Electrons: Structural Dependence and Implications to PFAS Remediation and Management.” Environmental Science & Technology 53 (7):3718-3728. 10.1021/acs.est.8b06648.

Beser, Maria Isabel, Olga Pardo, Joaquim Beltrán, and Vicent Yusà. 2011. “Determination of per- and polyfluorinated substances in airborne particulate matter by microwave-assisted extraction and liquid chromatography–tandem mass spectrometry.” Journal of Chromatography A 1218 (30):4847-4855. https://doi.org/10.1016/j.chroma.2011.04.082.

Besis, Athanasios, Elisavet Botsaropoulou, Constantini Samara, Athanasios Katsoyiannis, Linda Hanssen, and Sandra Huber. 2019. “Perfluoroalkyl substances (PFASs) in air-conditioner filter dust of indoor microenvironments in Greece: Implications for exposure.” Ecotoxicology and Environmental Safety 183:109559. https://doi.org/10.1016/j.ecoenv.2019.109559.

Beškoski, Vladimir P., Shusuke Takemine, Takeshi Nakano, Latinka Slavković Beškoski, Gordana Gojgić-Cvijović, Mila Ilić, Srdjan Miletić, and Miroslav M. Vrvić. 2013. “Perfluorinated compounds in sediment samples from the wastewater canal of Pančevo (Serbia) industrial area.” Chemosphere 91 (10):1408-1415. https://doi.org/10.1016/j.chemosphere.2012.12.079.

Bhattarai, B., M. Manickavachagam, and R.P.S. Suri. 2014. Development of Regenerable Adsorbents for the Removal of

Emerging Contaminants from Water. NSF Water and Environmental Technology Center.

Bhhatarai, Barun, and Paola Gramatica. 2011. “Prediction of Aqueous Solubility, Vapor Pressure and Critical Micelle Concentration for Aquatic Partitioning of Perfluorinated Chemicals.” Environmental Science & Technology 45 (19):8120-8128. https://doi.org/10.1021/es101181g.

Bhhatarai, Barun, and Paola Gramatica. 2012. “Correction to Prediction of Aqueous Solubility, Vapor Pressure and Critical Micelle Concentration for Aquatic Partitioning of Perfluorinated Chemicals.” Environmental Science & Technology 46 (1):566-566. https://doi.org/10.1021/es2042993.

Bickerstaff, Karen. 2004. “Risk perception research: socio-cultural perspectives on the public experience of air pollution.” Environment International 30 (6):827-840. https://doi.org/10.1016/j.envint.2003.12.001.

Biegel, L. B., M. E. Hurtt, S. R. Frame, J. C. O’Connor, and J. C. Cook. 2001. “Mechanisms of extrahepatic tumor induction by peroxisome proliferators in male CD rats.” Toxicol Sci 60 (1):44-55. 10.1093/toxsci/60.1.44.

Bijland, S., P. C. Rensen, E. J. Pieterman, A. C. Maas, J. W. van der Hoorn, M. J. van Erk, L. M. Havekes, K. Willems van Dijk, S. C. Chang, D. J. Ehresman, J. L. Butenhoff, and H. M. Princen. 2011. “Perfluoroalkyl sulfonates cause alkyl chain length-dependent hepatic steatosis and hypolipidemia mainly by impairing lipoprotein production in APOE*3-Leiden CETP mice.” Toxicol Sci 123 (1):290-303. 10.1093/toxsci/kfr142.

Bil, Wieneke, Marco Zeilmaker, Styliani Fragki, Johannes Lijzen, Eric Verbruggen, and Bas Bokkers. 2021. “Risk Assessment of Per- and Polyfluoroalkyl Substance Mixtures: A Relative Potency Factor Approach.” Environmental Toxicology and Chemistry 40 (3):859-870. https://doi.org/10.1002/etc.4835.

Birk, G. 2015. “RemBind Remediation of PFAS.” Tersus Environmental Webinar Series. http://tersusenv.com/en/resources/library/webinars/182-rembind/file.

Birk, G., and D. Alden. 2017. “Ex Situ Treatments of Aqueous Film-Forming Foam Impacted Water.” Fourth International Symposium on Bioremediation and Sustainable Environmental Technologies.

Bischel, H. N., L. A. Macmanus-Spencer, C. Zhang, and R. G. Luthy. 2011. “Strong associations of short-chain perfluoroalkyl acids with serum albumin and investigation of binding mechanisms.” Environ Toxicol Chem 30 (11):2423-30. https://doi.org/10.1002/etc.647.

Björklund, Justina Awasum, Kaj Thuresson, and Cynthia A. de Wit. 2009. “Perfluoroalkyl Compounds (PFCs) in Indoor Dust: Concentrations, Human Exposure Estimates, and Sources.” Environmental Science & Technology 43 (7):2276-2281. 10.1021/es803201a.

Blaine, A. C., C. D. Rich, L. S. Hundal, C. Lau, M. A. Mills, K. M. Harris, and C. P. Higgins. 2013. “Uptake of Perfluoroalkyl Acids into Edible Crops via Land Applied Biosolids: Field and Greenhouse Studies.” Environmental Science and Technology 47 (24):14062-14069. https://doi.org/10.1021/es403094q.

Blaine, Andrea C., Courtney D. Rich, Erin M. Sedlacko, Lakhwinder S. Hundal, Kuldip Kumar, Christopher Lau, Marc A. Mills, Kimberly M. Harris, and Christopher P. Higgins. 2014. “Perfluoroalkyl Acid Distribution in Various Plant Compartments of Edible Crops Grown in Biosolids-Amended soils.” Environmental Science & Technology 48 (14):7858-7865. https://doi.org/10.1021/es500016s.

Blaine, Andrea C., Courtney D. Rich, Erin M. Sedlacko, Katherine C. Hyland, Cecil Stushnoff, Eric R. V. Dickenson, and Christopher P. Higgins. 2014. “Perfluoroalkyl Acid Uptake in Lettuce (Lactuca sativa) and Strawberry (Fragaria ananassa) Irrigated with Reclaimed Water.” Environmental Science & Technology 48 (24):14361-14368. https://doi.org/10.1021/es504150h.

Blanc, Mélanie, Anna Kärrman, Petr Kukucka, Nikolai Scherbak, and Steffen Keiter. 2017. “Mixture-specific gene expression in zebrafish (Danio rerio) embryos exposed to perfluorooctane sulfonic acid (PFOS), perfluorohexanoic acid (PFHxA) and 3,3′,4,4′,5-pentachlorobiphenyl (PCB126).” Science of The Total Environment 590-591:249-257. https://doi.org/10.1016/j.scitotenv.2017.02.232.

Blotevogel, J., R.J. Giraud, and T. Borch. 2018. “Reductive defluorination of perfluorooctanoic acid by zero-valent iron and zinc: A DFT-based kinetic model.” Chemical Engineering Journal 335:248-254.

https://doi.org/10.1016/j.cej.2017.10.131.

Blum, A., S. A. Balan, M. Scheringer, X. Trier, G. Goldenman, I. T. Cousins, M. Diamond, T. Fletcher, C. Higgins, A. E. Lindeman, G. Peaslee, P. de Voogt, Z. Wang, and R. Weber. 2015. "The Madrid statement on poly- and perfluoroalkyl substances (PFASs)." Environmental Health Perspectives 123 (5):A107 – A111. http://dx.doi.org/10.1289/ehp.1509934.

Bock, Michael J., Lauren E. Brown, Richard J. Wenning, and Jennifer L. Bell. 2021. "Sources of 2,3,7,8-Tetrachlorodibenzo-p-dioxin and Other Dioxins in Lower Passaic River, New Jersey, Sediments." Environmental Toxicology and Chemistry 40 (5):1499-1519. https://doi.org/10.1002/etc.4974.

Bock. M, N. Rose, and T. Negley. 2022. "The "unique" challenges associated with applying statistical fingerprinting to PFAS." Battelle: Twelfth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Palm Springs, CA, May 22-26.

Bodin, Ö., and C. Prell. 2011. Social networks and natural resource management: Uncovering the social fabric of environmental governance. Cambridge, United Kingdom: Cambridge University Press. ISBN No. 978-0521146234.

Bodin, Ö., S. Ramirez-Sanchez, H. Ernstson, and C. Prell. 2011. "A social relational approach to natural resource governance." In Social networks and natural resource management: Uncovering the social fabric of environmental governance, edited by Ö. Bodin and C. Prell, 3-28. Cambridge, United Kingdom: Cambridge University Press. ISBN No. 978-0521146234.

Bogaerts, A., E. Neyts, R. Gijbels, and J. van der Mullen. 2002. "Gas discharge plasmas and their applications." Spectrochimica Acta 57 (4):609-658. https://doi.org/10.1016/S0584-8547(01)00406-2.

Bogdanska, Jasna, Daniel Borg, Maria Sundström, Ulrika Bergström, Krister Halldin, Manuchehr Abedi-Valugerdi, Åke Bergman, Buck Nelson, Joseph DePierre, and Stefan Nobel. 2011. "Tissue distribution of 35S-labelled perfluorooctane sulfonate in adult mice after oral exposure to a low environmentally relevant dose or a high experimental dose." Toxicology 284 (1):54-62. https://doi.org/10.1016/j.tox.2011.03.014.

Boiteux, V., X. Dauchy, C. Bach, A. Colin, J. Hemard, V. Sagres, and J. F. Munoz. 2017. "Concentrations and patterns of perfluoroalkyl and polyfluoroalkyl substances in a river and three drinking water treatment plants near and far from a major production source." Science of the Total Environment 583:393-400. https://doi.org/10.1016/j.scitotenv.2017.01.079.

Bolan, Nanthi, Binoy Sarkar, Meththika Vithanage, Gurwinder Singh, Daniel C. W. Tsang, Raj Mukhopadhyay, Kavitha Ramadass, Ajayan Vinu, Yuqing Sun, Sammani Ramanayaka, Son A. Hoang, Yubo Yan, Yang Li, Jörg Rinklebe, Hui Li, and M. B. Kirkham. 2021. "Distribution, behaviour, bioavailability and remediation of poly- and per-fluoroalkyl substances (PFAS) in solid biowastes and biowaste-treated soil." Environment International 155:106600. https://doi.org/10.1016/j.envint.2021.106600.

Bond, Rick, and Srinivas Veerapaneni. 2008. "Zeroing in on ZLD Technologies for Inland Desalination." Journal AWWA 100 (9):76-89. https://doi.org/10.1002/j.1551-8833.2008.tb09722.x.

Boo, Chanhee, Yunkun Wang, Ines Zucker, Youngwoo Choo, Chinedum O. Osuji, and Menachem Elimelech. 2018. "High Performance Nanofiltration Membrane for Effective Removal of Perfluoroalkyl Substances at High Water Recovery." Environmental Science & Technology 52 (13):7279-7288. 10.1021/acs.est.8b01040.

Boodoo, F. 2018. "Single-Use PFAS-Selective Resin + Incineration." Emerging Contaminants Summit.

Boodoo, F., J. Campos, and S. Kennedy. 2017. "Removal of PFOA, PFOS and other PFAS substances with ion exchange." International Water Conferences.

Bookstaff, R. C., R. W. Moore, G. B. Ingall, and R. E. Peterson. 1990. "Androgenic deficiency in male rats treated with perfluorodecanoic acid." Toxicol Appl Pharmacol 104 (2):322-33.

Borthakur, Annesh, Jamie Leonard, Vera S. Koutnik, Sujith Ravi, and Sanjay K. Mohanty. 2022. "Inhalation risks of wind-blown dust from biosolid-applied agricultural lands: Are they enriched with microplastics and PFAS?" Current Opinion in Environmental Science & Health 25:100309. https://doi.org/10.1016/j.coesh.2021.100309.

Borthakur, Annesh, Patience Olsen, Gregory P. Dooley, Brian K. Cranmer, Unnati Rao, Eric M. V. Hoek, Jens Blotevogel, Shaily Mahendra, and Sanjay K. Mohanty. 2021. “Dry-wet and freeze-thaw cycles enhance PFOA leaching from subsurface soils.” Journal of Hazardous Materials Letters 2:100029. https://doi.org/10.1016/j.hazl.2021.100029.

Borthakur, Annesh, Meng Wang, Meng He, Katia Ascencio, Jens Blotevogel, David T. Adamson, Shaily Mahendra, and Sanjay K. Mohanty. 2021. “Perfluoroalkyl acids on suspended particles: Significant transport pathways in surface runoff, surface waters, and subsurface soils.” Journal of Hazardous Materials 417:126159. https://doi.org/10.1016/j.jhazmat.2021.126159.

Bossi, R., K. Vorkamp, and H. Skov. 2016. “Concentrations of organochlorine pesticides, polybrominated diphenyl ethers and perfluorinated compounds in the atmosphere of North Greenland.” Environmental Pollution 217:4-10. https://doi.org/10.1016/j.envpol.2015.12.026.

Bots, Jessica, Luc De Bruyn, Tom Snijkers, Bert Van den Branden, and Hans Van Gossum. 2010. “Exposure to perfluorooctane sulfonic acid (PFOS) adversely affects the life-cycle of the damselfly Enallagma cyathigerum.” Environmental Pollution 158 (3):901-905. https://doi.org/10.1016/j.envpol.2009.09.016.

Botzen, W. J. W., J. C. J. H. Aerts, and J. C. J. M. Van Den Bergh. 2009. “Dependence of flood risk perceptions on socioeconomic and objective risk factors.” Water Resources Research 45:W10440. 10.1029/2009WR007743.

Boudreau, T. M., P. K. Sibley, S. A. Mabury, D. G. C. Muir, and K. R. Solomon. 2003. “Laboratory Evaluation of the Toxicity of Perfluorooctane Sulfonate (PFOS) on Selenastrum capricornutum, Chlorella vulgaris, Lemna gibba, Daphnia magna, and Daphnia pulicaria.” Archives of Environmental Contamination and Toxicology 44 (3):0307-0313. 10.1007/s00244-002-2102-6.

Boulanger, B., J. D. Vargo, J. L. Schnoor, and K. C. Hornbuckle. 2005. “Evaluation of Perfluorooctane Surfactants in a Wastewater Treatment System and in a Commercial Surface Protection Product.” Environmental Science and Technology 39 (15):5524-5530. https://doi.org/10.1021/es050213u.

Bowman Jessica, S. 2015. “Fluorotechnology Is Critical to Modern Life: The FluoroCouncil Counterpoint to the Madrid Statement.” Environmental Health Perspectives 123 (5):A112-A113. 10.1289/ehp.1509910.

Brake, Heather D., Antonia Langfeldt, John B. Kaneene, and Melinda J. Wilkins. 2023. “Current per- and polyfluoroalkyl substance (PFAS) research points to a growing threat in animals.” Journal of the American Veterinary Medical Association:1-7. 10.2460/javma.22.12.0582.

Brandsma, Sicco H., Marla Smithwick, Keith Solomon, Jeff Small, Jacob de Boer, and Derek C. G. Muir. 2011. “Dietary exposure of rainbow trout to 8:2 and 10:2 fluorotelomer alcohols and perfluorooctanesulfonamide: Uptake, transformation and elimination.” Chemosphere 82 (2):253-258. https://doi.org/10.1016/j.chemosphere.2010.09.050.

Bräunig, Jennifer, Christine Baduel, Amy Heffernan, Anna Rotander, Eric Donaldson, and Jochen F. Mueller. 2017. “Fate and redistribution of perfluoroalkyl acids through AFFF-impacted groundwater.” Science of The Total Environment 596-597:360-368. https://doi.org/10.1016/j.scitotenv.2017.04.095.

Bräunig, J., C. Baduel, and J. F. Mueller. 2016. Influence of a commercial adsorbent on the leaching behavior and bioavailability of selected perfluoroalkyl acids (PFAAs) from soil impacted by AFFF. Brisbane, Australia: National Research Center for Environmental Toxicology The University of Queensland.

Brede, E., M. Wilhelm, T. Goen, J. Muller, K. Rauchfuss, M. Kraft, and J. Holzer. 2010. “Two-year follow-up biomonitoring pilot study of residents’ and controls’ PFC plasma levels after PFOA reduction in public water system in Arnsberg, Germany.” Int J Hyg Environ Health 213 (3):217-23. 10.1016/j.ijheh.2010.03.007.

Brendel, Stephan, Éva Fetter, Claudia Staude, Lena Vierke, and Annegret Biegel-Engler. 2018. “Short-chain perfluoroalkyl acids: environmental concerns and a regulatory strategy under REACH.” Environmental Sciences Europe 30 (1):9. https://doi.org/10.1186/s12302-018-0134-4.

Brereton, R.G. 2009. Chemometrics for Pattern Recognition. New York: John Wiley & Sons, Ltd. ISBN No. 9780470987254.

Brewer, J. 2017. “Granular Activated Carbon: A Proven Solution for PFAS Treatment.” Cleanup Conference, Melbourne, Australia 8E.2. https://www.cleanupconference.com/past-event/.

Briggs, K., and D. Staack. 2015. “Enhancement of bioremediation of soils contaminated with organic hydrocarbon using an electron beam.” Third International Symposium on Bioremediation and Sustainable Environmental Technologies, Miami, Florida, May 18-21.

Brignole, A.J., J.R. Porch, H.O. Krueger, and R.L. Van Hoven. 2003. PFOS: a toxicity test to determine the effects of the test substance on seedling emergence of seven species of plants. Toxicity to Terrestrial Plants. EPA Docket AR226-1369. . Easton, MD: Ltd. Wildlife International.

Brooke, D., A. Footitt, and T. A. Nwaogu. 2004. Environmental Risk Evaluation Report: Perfluorooctanesulphonate (PFOS). Section 2: General Information on Exposure. Wallingford, UK: Environment Agency. http://www.environment-agency.gov.uk/.

Brown, Juliane B., Jason M. Conder, Jennifer A. Arblaster, and Christopher P. Higgins. 2020. “Assessing Human Health Risks from Per- and Polyfluoroalkyl Substance (PFAS)-Impacted Vegetable Consumption: A Tiered Modeling Approach.” Environmental Science & Technology 54 (23):15202-15214. 10.1021/acs.est.0c03411.

Brown, Sophia R., R. Wesley Flynn, and Jason T. Hoverman. 2021. “Perfluoroalkyl Substances Increase Susceptibility of Northern Leopard Frog Tadpoles to Trematode Infection.” Environmental Toxicology and Chemistry 40 (3):689-694. https://doi.org/10.1002/etc.4678.

Brusseau, Mark L. 2018. “Assessing the potential contributions of additional retention processes to PFAS retardation in the subsurface.” Science of The Total Environment 613-614:176-185. https://doi.org/10.1016/j.scitotenv.2017.09.065.

Brusseau, Mark L. 2019. “The influence of molecular structure on the adsorption of PFAS to fluid-fluid interfaces: Using QSPR to predict interfacial adsorption coefficients.” Water Research 152:148-158. https://doi.org/10.1016/j.watres.2018.12.057.

Brusseau, Mark L. 2019. “Estimating the relative magnitudes of adsorption to solid-water and air/oil-water interfaces for per- and poly-fluoroalkyl substances.” Environmental Pollution 254:113102. https://doi.org/10.1016/j.envpol.2019.113102.

Brusseau, Mark L. 2020. “Simulating PFAS transport influenced by rate-limited multi-process retention.” Water Research 168:115179. https://doi.org/10.1016/j.watres.2019.115179.

Brusseau, Mark L., R. Hunter Anderson, and Bo Guo. 2020. “PFAS concentrations in soils: Background levels versus contaminated sites.” Science of The Total Environment 740:140017. https://doi.org/10.1016/j.scitotenv.2020.140017.

Brusseau, Mark L., and Bo Guo. 2021. “Air-water interfacial areas relevant for transport of per and poly-fluoroalkyl substances.” Water Research 207:117785. https://doi.org/10.1016/j.watres.2021.117785.

Brusseau, M. L., and B. Guo. 2022. “PFAS concentrations in soil versus soil porewater: Mass distributions and the impact of adsorption at air-water interfaces.” Chemosphere 302:134938. https://doi.org/10.1016/j.chemosphere.2022.134938.

Brusseau, Mark L., Naima Khan, Yake Wang, Ni Yan, Sarah Van Glubt, and Kenneth C. Carroll. 2019. “Nonideal Transport and Extended Elution Tailing of PFOS in Soil.” Environmental Science & Technology 53 (18):10654-10664. https://doi.org/10.1021/acs.est.9b02343.

Brusseau, Mark L., and Sarah Van Glubt. 2021. “The influence of molecular structure on PFAS adsorption at air-water interfaces in electrolyte solutions.” Chemosphere 281:130829. https://doi.org/10.1016/j.chemosphere.2021.130829.

Brusseau, Mark L., Ni Yan, Sarah Van Glubt, Yake Wang, Wei Chen, Ying Lyu, Barry Dungan, Kenneth C. Carroll, and F. Omar Holguin. 2019. “Comprehensive retention model for PFAS transport in subsurface systems.” Water Research 148:41-50. https://doi.org/10.1016/j.watres.2018.10.035.

Bruton, Thomas A., and David L. Sedlak. 2017. “Treatment of Aqueous Film-Forming Foam by Heat-Activated Persulfate

Under Conditions Representative of In Situ Chemical Oxidation." Environmental Science & Technology 51 (23):13878-13885. 10.1021/acs.est.7b03969.

Buck, R.C. 2015. "Toxicology Data for Alternative " Short-Chain " Fluorinated Substances." In Toxicological Effects of Perfluoroalkyl and Polyfluoroalkyl Substances, edited by J.C. DeWitt. Humana Press, Cham. ISBN No. 978-3-319-15517-3.

Buck, Robert C., James Franklin, Urs Berger, Jason M. Conder, Ian T. Cousins, Pim de Voogt, Allan Astrup Jensen, Kurunthachalam Kannan, Scott A. Mabury, and Stefan P. J. van Leeuwen. 2011. "Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins." Integrated Environmental Assessment and Management 7 (4):513-541. https://doi.org/10.1002/ieam.258.

Buck, Robert C., Stephen H. Korzeniowski, Evan Laganis, and Frank Adamsky. 2021. "Identification and classification of commercially relevant per- and poly-fluoroalkyl substances (PFAS)." Integrated Environmental Assessment and Management 17 (5):1045-1055. https://doi.org/10.1002/ieam.4450.

Buckley, Thomas, Kavitha Karanam, Han Han, Hoang Nhat Phong Vo, Pradeep Shukla, Mahshid Firouzi, and Victor Rudolph. 2022. "Effect of different co-foaming agents on PFAS removal from the environment by foam fractionation." Water Research:119532. https://doi.org/10.1016/j.watres.2022.119532.

Buckley, Thomas, Kavitha Karanam, Han Han, Hoang Nhat Phong Vo, Pradeep Shukla, Mahshid Firouzi, and Victor Rudolph. 2023. "Effect of different co-foaming agents on PFAS removal from the environment by foam fractionation." Water Research 230:119532. https://doi.org/10.1016/j.watres.2022.119532.

Buckley, Thomas, Xiaoyong Xu, Victor Rudolph, Mahshid Firouzi, and Pradeep Shukla. 2021. "Review of foam fractionation as a water treatment technology." Separation Science and Technology:1-30. 10.1080/01496395.2021.1946698.

Burdick, J., I. Ross, J. McDonough, J. Miles, and K. Nowack. 2016. "Poly- and Perfluouroalkyl Substances (PFAS) Treatment: State of the Practice and Mythbusting." Impacts from Fire Fighting Foams: Policy, Regulation, Characterization and Treatment for PFCs, USEPA and the Society of American Military Engineers.

Burger, J., and M. Gochfeld. 1991. "Fishing a superfund site: dissonance and risk perception of environmental hazards by fishermen in Puerto Rico." Risk Analysis 11:269-722. https://doi.org/10.1111/j.1539-6924.1991.tb00603.x.

Burkhard, Lawrence P. 2003. "Factors influencing the design of bioaccumulation factor and biota-sediment accumulation factor field studies." Environmental Toxicology and Chemistry 22 (2):351-360. https://doi.org/10.1002/etc.5620220216.

Burkhard, Lawrence P. 2021. "Evaluation of Published Bioconcentration Factor (BCF) and Bioaccumulation Factor (BAF) Data for Per- and Polyfluoroalkyl Substances Across Aquatic Species." Environmental Toxicology and Chemistry 40 (6):1530-1543. https://doi.org/10.1002/etc.5010.

Burkhard, Lawrence P., Jon A. Arnot, Michelle R. Embry, Kevin J. Farley, Robert A. Hoke, Masaru Kitano, Heather A. Leslie, Guilherme R. Lotufo, Thomas F. Parkerton, Keith G. Sappington, Gregg T. Tomy, and Kent B. Woodburn. 2012. "Comparing laboratory and field measured bioaccumulation endpoints." Integrated Environmental Assessment and Management 8 (1):17-31. https://doi.org/10.1002/ieam.260.

Burki, Richard, Etiënne L. M. Vermeirssen, Oliver Körner, Caroline Joris, Patricia Burkhardt-Holm, and Helmut Segner. 2006. "Assessment of estrogenic exposure in brown trout (Salmo trutta) in a Swiss midland river: Integrated analysis of passive samplers, wild and caged fish, and vitellogenin mRNA and protein." Environmental Toxicology and Chemistry 25 (8):2077-2086. https://doi.org/10.1897/05-545R.1.

Burns, Darcy C., David A. Ellis, Hongxia Li, Colin J. McMurdo, and Eva Webster. 2008. "Experimental pKa Determination for Perfluorooctanoic Acid (PFOA) and the Potential Impact of pKa Concentration Dependence on Laboratory-Measured Partitioning Phenomena and Environmental Modeling." Environmental Science & Technology 42 (24):9283-9288. 10.1021/es802047v.

Burns, David J., Helena M. Hinrichsen, Paul Stevenson, and Peter J. C. Murphy. 2022. "Commercial-scale remediation of per- and polyfluoroalkyl substances from a landfill leachate catchment using Surface-Active Foam Fractionation

(SAFF®).” Remediation Journal 32 (3):139-150. https://doi.org/10.1002/rem.21720.

Burns, David J., Paul Stevenson, and Peter J. C. Murphy. 2021. “PFAS removal from groundwaters using Surface-Active Foam Fractionation.” Remediation Journal 1-15. https://doi.org/10.1002/rem.21694.

Bursian, Steven J., Jane E. Link, Michael McCarty, and Matt F. Simcik. 2021. “The Subacute Toxicity of Perfluorooctane Sulfonate and/or Perfluorooctanoic Acid and Legacy Aqueous Film-Forming Foams to Japanese Quail (Coturnix japonica) Chicks.” Environmental Toxicology and Chemistry 40:695-710. https://doi.org/10.1002/etc.4684.

Busch, Jan, Lutz Ahrens, Renate Sturm, and Ralf Ebinghaus. 2010. “Polyfluoroalkyl compounds in landfill leachates.” Environmental Pollution 158 (5):1467-1471. https://doi.org/10.1016/j.envpol.2009.12.031.

Butenhoff, J., and S. Chang. 2007. ADME Study of Perfluorooctane Sulfonate in Rats, (cited in EPA, 2016d). ST-179 Final Report. St. Paul, MN: 3M Center 3M Strategic Toxicology Laboratory.

Butenhoff, J., G. Costa, C. Elcombe, D. Farrar, K. Hansen, H. Iwai, R. Jung, G. Kennedy, Jr., P. Lieder, G. Olsen, and P. Thomford. 2002. “Toxicity of ammonium perfluorooctanoate in male cynomolgus monkeys after oral dosing for 6 months.” Toxicol Sci 69 (1):244-57. https://doi.org/10.1093/toxsci/69.1.244.

Butenhoff, J. L., J. A. Bjork, S. C. Chang, D. J. Ehresman, G. A. Parker, K. Das, C. Lau, P. H. Lieder, F. M. van Otterdijk, and K. B. Wallace. 2012. “Toxicological evaluation of ammonium perfluorobutyrate in rats: twenty-eight-day and ninety-day oral gavage studies.” Reprod Toxicol 33 (4):513-530. https://doi.org/10.1016/j.reprotox.2011.08.004.

Butenhoff, J. L., S. C. Chang, D. J. Ehresman, and R. G. York. 2009. “Evaluation of potential reproductive and developmental toxicity of potassium perfluorohexanesulfonate in Sprague Dawley rats.” Reprod Toxicol 27 (3-4):331-341. https://doi.org/10.1016/j.reprotox.2009.01.004.

Butenhoff, J. L., S. C. Chang, G. W. Olsen, and P. J. Thomford. 2012. “Chronic dietary toxicity and carcinogenicity study with potassium perfluorooctanesulfonate in Sprague Dawley rats.” Toxicology 293 (1-3):1-15. https://doi.org/10.1016/j.tox.2012.01.003.

Butenhoff, J. L., D. W. Gaylor, J. A. Moore, G. W. Olsen, J. Rodricks, J. H. Mandel, and L. R. Zobel. 2004. “Characterization of risk for general population exposure to perfluorooctanoate.” Regul Toxicol Pharmacol 39 (3):363-80. https://doi.org/10.1016/j.yrtph.2004.03.003.

Butenhoff, J. L., G. L. Kennedy, Jr., S. C. Chang, and G. W. Olsen. 2012. “Chronic dietary toxicity and carcinogenicity study with ammonium perfluorooctanoate in Sprague-Dawley rats.” Toxicology 298 (1-3):1-13. https://doi.org/10.1016/j.tox.2012.04.001.

Butenhoff, J. L., G. L. Kennedy, Jr., S. R. Frame, J. C. O’Connor, and R. G. York. 2004. “The reproductive toxicology of ammonium perfluorooctanoate (APFO) in the rat.” Toxicology 196 (1-2):95-116. https://doi.org/10.1016/j.tox.2003.11.005.

Butenhoff, J. L., G. L. Kennedy, Jr., P. M. Hinderliter, P. H. Lieder, R. Jung, K. J. Hansen, G. S. Gorman, P. E. Noker, and P. J. Thomford. 2004. “Pharmacokinetics of perfluorooctanoate in cynomolgus monkeys.” Toxicol Sci 82 (2):394-406. https://doi.org/10.1093/toxsci/kfh302.

Butt, Craig M., Urs Berger, Rossana Bossi, and Gregg T. Tomy. 2010. “Levels and trends of poly- and perfluorinated compounds in the arctic environment.” Science of The Total Environment 408 (15):2936-2965. https://doi.org/10.1016/j.scitotenv.2010.03.015.

Butt, Craig M., Scott A. Mabury, Michael Kwan, Xiaowa Wang, and Derek C. G. Muir. 2008. “Spatial trends of perfluoroalkyl compounds in ringed seals (Phoca hispida) from the Canadian Arctic.” Environmental Toxicology and Chemistry 27 (3):542-553. https://doi.org/10.1897/07-428.1.

Butt, Craig M., Derek C.G. Muir, and Scott A. Mabury. 2010. “Elucidating the Pathways of Poly- and Perfluorinated Acid Formation in Rainbow Trout.” Environmental Science & Technology 44 (13):4973-80. https://doi.org/10.1021/es100702a.

Butt, Craig M., Derek C. G. Muir, and Scott A. Mabury. 2014. “Biotransformation pathways of fluorotelomer-based polyfluoroalkyl substances: A review." Environmental Toxicology and Chemistry 33 (2):243-267. http://dx.doi.org/10.1002/etc.2407.

Buxton, G. V., C.L. Greenstock, W. P. W. P. Helman, and A. B. Ross. 1988. "Critical review of rate constants for reactions of hydrated electrons, hydrogen atoms and hydroxyl radicals in aqueous solution." Journal of Physical and Chemical Reference Data 17:513.

Byrne, Samuel, Samarys Seguinot-Medina, Pamela Miller, Vi Waghiyi, Frank A. von Hippel, C. Loren Buck, and David O. Carpenter. 2017. "Exposure to polybrominated diphenyl ethers and perfluoroalkyl substances in a remote population of Alaska Natives." Environmental Pollution 231:387-395. https://doi.org/10.1016/j.envpol.2017.08.020.

Byrne, S.C. 2009. Persistent Organic Pollutants in the Arctic. A Report for the Delegates of the 4th Conference of the Parties. Stockholm Convention on Persistent Organic Pollutants. Anchorage, AK: Alaska Community Action on Toxics (ACAT). https://www.akaction.org/wp-content/uploads/2013/03/POPs_in_the_Arctic_ACAT_May_2009.pdf.

C8 Science Panel. 2011. Probable Link Evaluation of Pregnancy Induced Hypertension and Preeclampsia. http://www.c8sciencepanel.org/pdfs/Probable_Link_C8_PIH_5Dec2011.pdf

C8 Science Panel. 2012. Probable Link Evaluation for heart disease (including high blood pressure, high cholesterol, coronary artery disease). http://www.c8sciencepanel.org/pdfs/Probable_Link_C8_Heart_Disease_29Oct2012.pdf

C8 Science Panel. 2012. Probable Link Evaluation of Thyroid disease. http://www.c8sciencepanel.org/pdfs/Probable_Link_C8_Thyroid_30Jul2012.pdf

C8 Science Panel. 2012. Probable Link Evaluation of Autoimmune Disease. http://www.c8sciencepanel.org/pdfs/Probable_Link_C8_Autoimmune_Disease_30Jul2012.pdf

C8 Science Panel. 2012. Probable Link Evaluation of Cancer. http://www.c8sciencepanel.org/pdfs/Probable_Link_C8_Cancer_16April2012_v2.pdf.

C8 Science Panel. 2017. "C8 Probable Links Reports." http://www.c8sciencepanel.org/prob_link.html.

C8 Science Panel. 2020. "C8 Science Panel website." Last Modified 1/22/2020. http://www.c8sciencepanel.org.

CA DTSC. 2019. Product – Chemical Profile for Treatments Containing Perfluoroalkyl or Polyfluoroalkyl Substances for Use on Converted Textiles or Leathers. Discussion Draft. https://dtsc.ca.gov/wp-content/uploads/sites/31/2019/11/Product-Chemical-Profile-for-Treatments-with-PFASs.pdf.

CA DTSC. 2019. Work Plan Implementation: Food Packaging with Perfluoroalkyl and Polyfluoroalkyl Substances (PFASs). https://dtsc.ca.gov/wp-content/uploads/sites/31/2019/10/Food-Packaging_Perfluoroalkyl-and-Polyfluoroalkyl-Substances-PFASs.pdf.

CA DTSC. 2021. "Effective July 1, 2021: Carpets and Rugs with Perfluoroalkyl or Polyfluoroalkyl Substances (PFASs)." accessed 2021. https://dtsc.ca.gov/scp/carpets-and-rugs-with-perfluoroalkyl-and-polyfluoroalkyl-substances-pfass/.

CA DTSC. 2021. "Proposed Priority Product: Treatments Containing Perfluoroalkyl or Polyfluoroalkyl Substances for Use on Converted Textiles or Leathers." accessed 2021. https://dtsc.ca.gov/scp/treatments-with-pfass/.

CA DTSC. 2021. "Proposed Priority Product: Food Packaging Containing Perfluoroalkyl or Polyfluoroalkyl Substances." accessed 2021. https://dtsc.ca.gov/scp/food-packaging-containing-pfass/.

CA OEHHA. 2011. Results for Perfluorochemicals (PFCs). Biomonitoring California. https://biomonitoring.ca.gov/results/chemical/154%2011.

CA OEHHA. 2012. California Teachers Study (CTS) and Firefighters Occupational Exposures (FOX) Project. Biomonitoring California. https://biomonitoring.ca.gov/results/chemical/154

CA OEHHA. 2013. California Teachers Study (CTS) Results – Perfluorochemicals (PFCs). Biomonitoring California. https://biomonitoring.ca.gov/downloads/california-teachers-study-cts-results-perfluorochemicals-pfcs

CA OEHHA. 2016. Notice of Intent to List Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonate (PFOS).

https://oehha.ca.gov/proposition-65/crnr/notice-intent-list-perfluorooctanoic-acid-pfoa-and-perfluorooctane-sulfonate.

CA OEHHA. 2018. "Chemicals Listed Effective November 10, 2017 as Known to the State of California to Cause Reproductive Toxicity: Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonate (PFOS)."

CA OEHHA. 2019. Notification Level Recommendations for Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonate (PFOS) in Drinking Water. California Environmental Protection Agency. https://oehha.ca.gov/media/downloads/water/chemicals/nl/final-pfoa-pfosnl082119.pdf.

CA OEHHA. 2020. "Biomonitoring California. Results for Perfluoroalkyl and Polyfluoroalkyl Substances (PFASs)." Last Modified 10/22/2020. accessed 2021. https://biomonitoring.ca.gov/results/chemical/2183.

CA OEHHA. 2023. Proposed Public Health Goals for Perfluorooctanoic Acid and Perfluorooctane Sulfonic Acid in Drinking Water. Second Public Review Draft. https://oehha.ca.gov/media/downloads/water/public-health-goal/pfoapfosseconddraft071423.pdf.

CA RWQCB. 2016. "Water Quality Control Plan for the Sacramento and San Joaquin River Basins." Central Valley Region.

CA Water Boards. 2019. Water Boards PFAS Phased Investigation Approach. https://www.waterboards.ca.gov/pfas/docs/7_investigation_plan.pdf.

CA Water Boards. 2021. "Per- and Polyfluoroalkyl Substances (PFAS)." Last Modified 8/12/2021. accessed 2021. https://www.waterboards.ca.gov/pfas/.

CA Water Boards. 2021. "CA PFAS Timeline." Last Modified 8/5/21. accessed 2021. https://www.waterboards.ca.gov/water_issues/programs/pfas/ca_pfas_timeline.html.

Cai, Dan, Qing-Qing Li, Chu Chu, Shi-Zhong Wang, Ye-Tao Tang, Allison A. Appleton, Rong-Liang Qiu, Bo-Yi Yang, Li-Wen Hu, Guang-Hui Dong, and Xiao-Wen Zeng. 2020. "High trans-placental transfer of perfluoroalkyl substances alternatives in the matched maternal-cord blood serum: Evidence from a birth cohort study." Science of The Total Environment 705:135885. https://doi.org/10.1016/j.scitotenv.2019.135885.

Cai, Minghong, Zhiyong Xie, Axel Möller, Zhigao Yin, Peng Huang, Minggang Cai, Haizhen Yang, Renate Sturm, Jianfeng He, and Ralf Ebinghaus. 2012. "Polyfluorinated compounds in the atmosphere along a cruise pathway from the Japan Sea to the Arctic Ocean." Chemosphere 87 (9):989-997. https://doi.org/10.1016/j.chemosphere.2011.11.010.

Cai, Minghong, Haizhen Yang, Zhiyong Xie, Zhen Zhao, Feng Wang, Zhibo Lu, Renate Sturm, and Ralf Ebinghaus. 2012. "Per- and polyfluoroalkyl substances in snow, lake, surface runoff water and coastal seawater in Fildes Peninsula, King George Island, Antarctica." Journal of Hazardous Materials 209-210:335-342. https://doi.org/10.1016/j.jhazmat.2012.01.030.

Cai, Minghong, Zhen Zhao, Zhigao Yin, Lutz Ahrens, Peng Huang, Minggang Cai, Haizhen Yang, Jianfeng He, Renate Sturm, Ralf Ebinghaus, and Zhiyong Xie. 2012. "Occurrence of Perfluoroalkyl Compounds in Surface Waters from the North Pacific to the Arctic Ocean." Environmental Science & Technology 46 (2):661-668. https://doi.org/10.1021/es2026278.

Cai, Wenwen, Divina A. Navarro, Jun Du, Guangguo Ying, Bin Yang, Mike J. McLaughlin, and Rai S. Kookana. 2022. "Increasing ionic strength and valency of cations enhance sorption through hydrophobic interactions of PFAS with soil surfaces." Science of The Total Environment 817:152975. https://doi.org/10.1016/j.scitotenv.2022.152975.

CalEPA. 2006. California Dry Cleaning Industry Technical Assessment Report. State of California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/classic/toxics/dryclean/finaldrycleantechreport.pdf.

CalEPA. 2018. "Product – Chemical Profile for Perfluoroalkyl and Polyfluroalkyl Substances (PFASs) in Carpets and Rugs February 2018 Discussion Draft."

CalEPA. 2021. First Public Review Draft. Proposed Public Health Goals for Perfluorooctanoic Acid and Perfluorooctane Sulfonic Acid in Drinking Water. OEHHA. https://oehha.ca.gov/media/downloads/crnr/pfoapfosphgdraft061021.pdf.

Calgon Corporation. 2017. "Treatment of Perfluorinated Compounds with Granular Activated Carbon." Eric Forrester of Calgon to the US Army Corps of Engineers.

California Assembly. 2022. Cosmetic Products: Safety. Bill 2771. https://legiscan.com/CA/text/AB2771/2021.

Campbell, Tammy, and Michael R. Hoffmann. 2015. “Sonochemical degradation of perfluorinated surfactants: Power and multiple frequency effects.” Separation and Purification Technology 156:1019-1027. https://doi.org/10.1016/j.seppur.2015.09.053.

Campo, Julian, María Lorenzo, Francisca Pérez, Yolanda Picó, Marinel la Farré, and Damià Barceló. 2016. “Analysis of the presence of perfluoroalkyl substances in water, sediment and biota of the Jucar River (E Spain). Sources, partitioning and relationships with water physical characteristics.” Environmental Research 147:503-512. https://doi.org/10.1016/j.envres.2016.03.010.

Campos Pereira, Hugo, Malin Ullberg, Dan Berggren Kleja, Jon Petter Gustafsson, and Lutz Ahrens. 2018. “Sorption of perfluoroalkyl substances (PFASs) to an organic soil horizon – Effect of cation composition and pH.” Chemosphere 207:183-191. https://doi.org/10.1016/j.chemosphere.2018.05.012.

Campos-Pereira, Hugo, Dan B. Kleja, Carin Sjöstedt, Lutz Ahrens, Wantana Klysubun, and Jon Petter Gustafsson. 2020. “The Adsorption of Per- and Polyfluoroalkyl Substances (PFASs) onto Ferrihydrite Is Governed by Surface Charge.” Environmental Science & Technology 54 (24):15722-15730. 10.1021/acs.est.0c01646.

Canada, Health. 2018. Guidelines for Canadian Drinking Water Quality: Guideline Technical Document: Perfluorooctane Sulfonate (PFOS). Ottawa, Ontario: Healthy Environments and Consumer Safety Branch Water and Air Quality Bureau, Health Canada.

Canada, Health. 2018. Guidelines for Canadian Drinking Water Quality: Guideline Technical Document: Perfluorooctanoic Acid (PFOA). Ottawa, Ontario: Healthy Environments and Consumer Safety Branch Water and Air Quality Bureau, Health Canada.

Cañizares, P., C. Sáez, J. Lobato, and M. A. Rodrigo. 2004. “Electrochemical Oxidation of Polyhydroxybenzenes on Boron-Doped Diamond Anodes.” Industrial & Engineering Chemistry Research 43 (21):6629-6637. https://doi.org/10.1021/ie049807g.

Cao, Huimin, Weilan Zhang, Cuiping Wang, and Yanna Liang. 2020. “Sonochemical degradation of poly- and perfluoroalkyl substances – A review.” Ultrasonics Sonochemistry 69:105245. https://doi.org/10.1016/j.ultsonch.2020.105245.

Cao, M. H., B. B. Wang, H. S. Yu, L. L. Wang, S. H. Yuan, and J. Chen. 2010. “Photochemical decomposition of perfluorooctanoic acid in aqueous periodate with VUV and UV light irradiation.” Journal of Hazardous Materials 179 (1):1143-1146. https://doi.org/10.1016/j.jhazmat.2010.02.030.

Cao, Xianghui, Chenchen Wang, Yonglong Lu, Meng Zhang, Kifayatullah Khan, Shuai Song, Pei Wang, and Cong Wang. 2019. “Occurrence, sources and health risk of polyfluoroalkyl substances (PFASs) in soil, water and sediment from a drinking water source area.” Ecotoxicology and Environmental Safety 174:208-217. https://doi.org/10.1016/j.ecoenv.2019.02.058.

Cappuyns, Valérie, and Bram Kessen. 2013. “Combining life cycle analysis, human health and financial risk assessment for the evaluation of contaminated site remediation.” Journal of Environmental Planning and Management 57 (7):1101-1121. https://doi.org/10.1080/09640568.2013.783460.

Carey, Grant R., Seyfollah G. Hakimabadi, Mantake Singh, Rick McGregor, Claire Woodfield, Paul J. Van Geel, and Anh Le-Tuan Pham. 2022. “Longevity of colloidal activated carbon for in situ PFAS remediation at AFFF-contaminated airport sites.” Remediation Journal 33 (1):3-23. https://doi.org/10.1002/rem.21741.

Carey, Grant R., Rick McGregor, Anh Le-Tuan Pham, Brent Sleep, and Seyfollah Gilak Hakimabadi. 2019. “Evaluating the longevity of a PFAS in situ colloidal activated carbon remedy.” Remediation Journal 29 (2):17-31. https://doi.org/10.1002/rem.21593.

Carey, G.R., P.J. Van Geel, J.R. Murphy, E.A. McBean, and F.A. Rovers. 1999. “Modeling natural attenuation at the Plattsburgh Air Force Base.” In Natural attenuation of chlorinated solvents, petroleum hydrocarbons, and other organic compounds, edited by B. C. Alleman and A. Leeson, 77-82. Columbus, OH: Battelle Press. ISBN No. 978-1574770742.

Carey, Grant R., Paul J. Van Geel, Todd H. Wiedemeier, and Edward A. McBean. 2003. “A Modified Radial Diagram Approach for Evaluating Natural Attenuation Trends for Chlorinated Solvents and Inorganic Redox Indicators.” Groundwater Monitoring & Remediation 23 (4):75-84. https://doi.org/10.1111/j.1745-6592.2003.tb00697.x.

Carlson, Gail L., and Skylar Tupper. 2020. “Ski wax use contributes to environmental contamination by per- and polyfluoroalkyl substances.” Chemosphere 261:128078. https://doi.org/10.1016/j.chemosphere.2020.128078.

Carlson Laura, M., Michelle Angrish, V. Shirke Avanti, G. Radke Elizabeth, Brittany Schulz, Andrew Kraft, Richard Judson, Grace Patlewicz, Robyn Blain, Cynthia Lin, Nicole Vetter, Courtney Lemeris, Pamela Hartman, Heidi Hubbard, Xabier Arzuaga, Allen Davis, V. Dishaw Laura, L. Druwe Ingrid, Hillary Hollinger, Ryan Jones, J. Phillip Kaiser, Lucina Lizarraga, D. Noyes Pamela, Michele Taylor, J. Shapiro Andrew, J. Williams Antony, and A. Thayer Kristina. 2022. “Systematic Evidence Map for Over One Hundred and Fifty Per- and Polyfluoroalkyl Substances (PFAS).” Environmental Health Perspectives 130 (5):056001. 10.1289/EHP10343.

Carmosini, N., and L. S. Lee. 2008. “Partitioning of Fluorotelomer Alcohols to Octanol and Different Sources of Dissolved Organic Carbon.” Environmental Science & Technology 42 (17):6559-6565. https://doi.org/10.1021/es800263t.

Carr, Caroline K., Andrew M. Watkins, Cynthia J. Wolf, Barbara D. Abbott, Christopher Lau, and Chris Gennings. 2013. “Testing for departures from additivity in mixtures of perfluoroalkyl acids (PFAAs).” Toxicology 306:169-175. https://doi.org/10.1016/j.tox.2013.02.016.

Carter, Kimberly E., and James Farrell. 2008. “Oxidative Destruction of Perfluorooctane Sulfonate Using Boron-Doped Diamond Film Electrodes.” Environmental Science & Technology 42 (16):6111-6115. https://doi.org/10.1021/es703273s.

Carter, Kimberly E., and James Farrell. 2009. “Electrochemical Oxidation of Trichloroethylene Using Boron-Doped Diamond Film Electrodes.” Environmental Science & Technology 43 (21):8350-8354. http://doi.org/10.1021/es9017738.

Casal, Paulo, Yifeng Zhang, Jonathan W. Martin, Mariana Pizarro, Begoña Jiménez, and Jordi Dachs. 2017. “Role of Snow Deposition of Perfluoroalkylated Substances at Coastal Livingston Island (Maritime Antarctica).” Environmental Science & Technology 51 (15):8460-8470. 10.1021/acs.est.7b02521.

Casas, Gemma, Alícia Martínez-Varela, Jose L. Roscales, Maria Vila-Costa, Jordi Dachs, and Begoña Jiménez. 2020. “Enrichment of perfluoroalkyl substances in the sea-surface microlayer and sea-spray aerosols in the Southern Ocean.” Environmental Pollution 267:115512. https://doi.org/10.1016/j.envpol.2020.115512.

Casas, Gemma, Alícia Martinez-Varela, Maria Vila-Costa, Begoña Jiménez, and Jordi Dachs. 2021. “Rain Amplification of Persistent Organic Pollutants.” Environmental Science & Technology 55 (19):12961-12972. 10.1021/acs.est.1c03295.

Case, M.T., R.G. York, and M.S. Christian. 2001. “Rat and rabbit oral developmental toxicology studies with two perfluorinated compounds.” Int J Toxicol 20 (2):101-9.

Cassone, C. G., V. Vongphachan, S. Chiu, K. L. Williams, R. J. Letcher, E. Pelletier, D. Crump, and S. W. Kennedy. 2012. “In ovo effects of perfluorohexane sulfonate and perfluorohexanoate on pipping success, development, mRNA expression, and thyroid hormone levels in chicken embryos.” Toxicol Sci 127 (1):216-24. https://doi.org/10.1093/toxsci/kfs072.

Caverly Rae, J. M., Lisa Craig, Theodore W. Slone, Steven R. Frame, L. William Buxton, and Gerald L. Kennedy. 2015. “Evaluation of chronic toxicity and carcinogenicity of ammonium 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)-propanoate in Sprague–Dawley rats.” Toxicology Reports 2:939-949. https://doi.org/10.1016/j.toxrep.2015.06.001.

CCME. 2018. Canadian Soil and Groundwater Quality Guidelines for the Protection of Environmental and Human Health, Perfluorooctane Sulfonate (PFOS) – Draft for Review. Canadian Council of Ministers of the Environment. https://www.watercanada.net/soil-and-groundwater-quality-guidelines-available-for-public-comment/.

CDC. 2016. “National Health and Nutrition Examination Survey. 2013-2014 Data Documentation, Codebook and Frequencies.” accessed 2020. https://wwwn.cdc.gov/nchs/nhanes/ContinuousNhanes/Default.aspx?BeginYear=2013.

CDC. 2017. Fourth National Report on Human Exposure to Environmental Chemicals, Updated Tables, Volume 1. https://www.cdc.gov/biomonitoring/pdf/FourthReport_UpdatedTables_Volume1_Jan2017.pdf.

CDC. 2017. National Biomonitoring Program Biomonitoring Summary Perfluorochemicals. https://www.cdc.gov/biomonitoring/PFAS_BiomonitoringSummary.html.

CDC. 2018. Fourth National Report on Human Exposure to Environmental Chemicals, Updated Tables, March 2018, Volume 1. U.S. Department of Health and Human Services. Centers for Disease Control and Prevention. https://www.cdc.gov/exposurereport/pdf/FourthReport_UpdatedTables_Volume1_Mar2018.pdf.

CDC. 2018. “Introduction to Public Health.” Last Modified November 15, 2018. accessed 2020. https://www.cdc.gov/publichealth101/public-health.html.

CDC. 2019. Fourth National Report on Human Exposure to Environmental Chemicals Updated Tables, January 2019. Volume One: U.S. Department of Health and Human Services. Centers for Disease Control and Prevention. https://www.cdc.gov/exposurereport/pdf/FourthReport_UpdatedTables_Volume1_Jan2019-508.pdf.

CDC. 2020. Emergency Preparedness & Vulnerable Populations: Planning for Those Most at Risk. https://www.cdc.gov/cpr/whatwedo/00_docs/Issue_Brief_Vulnerable_pops.pdf.

CDC. 2021. Early Release: Per- and Polyfluorinated Substances (PFAS) Tables, NHANES 2011-2018. Atlanta, GA: Centers for Disease Control and Prevention. https://www.cdc.gov/exposurereport/pfas_early_release.html.

CDC. 2022. National Report on Human Exposure to Environmental Chemicals. https://www.cdc.gov/exposurereport/index.html.

CDC. 2022. “Biomonitoring Data Tables for Environmental Chemicals.” Last Modified March 24, 2022. accessed 2023. https://www.cdc.gov/exposurereport/data_tables.html.

CEH. 2020. Fact Sheet, Fluorinated Additives, Disposable Food Containers, and Contaminated Food: State of the Evidence. www.ceh.org.

Cejas, Mark Jonathan, and Robert C. Barrick. 2020. “Chemometric mapping of polychlorinated dibenzo-p-dioxin (PCDD) and dibenzofuran (PCDF) congeners from the Passaic River, NJ: Integrated application of RSIMCA, PVA, and t-SNE.” Environmental Forensics 22:155 – 171.

CEPA. 2006. Environmental Performance Agreement (“Agreement”) Respecting Perfluorinated Carboxylic Acids (PFCAs) and their Precursors in Perfluorochemical Products Sold in Canada Environment and Climate Change Canada. https://www.canada.ca/en/environment-climate-change/services/environmental-performance-agreements/list/perfluorocarboxylic-acids-overview.html.

CEPA. 2017. Canadian Environmental Protection Act, 1999. Federal Environmental Quality Guidelines: Perfluorooctane Sulfonate (PFOS). Environment and Climate Change Canada. https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/federal-environmental-quality-guidelines-perfluorooctane-sulfonate.html.

CEPA. 2018. Toxic Substances list: PFOS. Environment and Climate Change Canada. https://www.canada.ca/en/environment-climate-change/services/management-toxic-substances/list-canadian-environmental-protection-act/perfluorooctane-sulfonate.html.

CH2M. 2017. PFAS Flocculation/Membrane Filtration Testing Results.: Technical 11279 Memorandum prepared for Environment Canada.

Chandramouli, Bharat, Jonathan P. Benskin, M. Coreen Hamilton, and John R. Cosgrove. 2015. “Sorption of per- and polyfluoroalkyl substances (PFASs) on filter media: Implications for phase partitioning studies.” Environmental Toxicology and Chemistry 34 (1):30-36. https://doi.org/10.1002/etc.2751.

Chang, E. T., H. O. Adami, P. Boffetta, P. Cole, T. B. Starr, and J. S. Mandel. 2014. “A critical review of perfluorooctanoate and perfluorooctanesulfonate exposure and cancer risk in humans.” Crit Rev Toxicol 44 Suppl 1:1-81. https://doi.org/10.3109/10408444.2014.905767.

Chang, E. T., H. O. Adami, P. Boffetta, H. J. Wedner, and J. S. Mandel. 2016. “A critical review of perfluorooctanoate and perfluorooctanesulfonate exposure and immunological health conditions in humans.” Crit Rev Toxicol 46 (4):279-331. https://doi.org/10.3109/10408444.2015.1122573.

Chang, S., J. L. Butenhoff, G. A. Parker, P. S. Coder, J. D. Zitzow, R. M. Krisko, J. A. Bjork, K. B. Wallace, and J. G. Seed. 2018. “Reproductive and developmental toxicity of potassium perfluorohexanesulfonate in CD-1 mice.” Reprod Toxicol 78:150-168. https://doi.org/10.1016/j.reprotox.2018.04.007.

Chang, Sue, Brian T. Mader, Kent R. Lindstrom, Cleston C. Lange, Jill A. Hart, Thomas A. Kestner, Jay F. Schulz, David J. Ehresman, and John L. Butenhoff. 2017. “Perfluorooctanesulfonate (PFOS) Conversion from N-Ethyl-N-(2-hydroxyethyl)-perfluorooctanesulfonamide (EtFOSE) in male Sprague Dawley rats after inhalation exposure.” Environmental Research 155:307-313. https://doi.org/10.1016/j.envres.2017.02.029.

Chang, S. C., K. Das, D. J. Ehresman, M. E. Ellefson, G. S. Gorman, J. A. Hart, P. E. Noker, Y. M. Tan, P. H. Lieder, C. Lau, G. W. Olsen, and J. L. Butenhoff. 2008. “Comparative pharmacokinetics of perfluorobutyrate in rats, mice, monkeys, and humans and relevance to human exposure via drinking water.” Toxicol Sci 104 (1):40-53. https://doi.org/10.1093/toxsci/kfn057.

Chang, S. C., P. E. Noker, G. S. Gorman, S. J. Gibson, J. A. Hart, D. J. Ehresman, and J. L. Butenhoff. 2012. “Comparative pharmacokinetics of perfluorooctanesulfonate (PFOS) in rats, mice, and monkeys.” Reprod Toxicol 33 (4):428-440. https://doi.org/10.1016/j.reprotox.2011.07.002.

Chang, S. C., J. R. Thibodeaux, M. L. Eastvold, D. J. Ehresman, J. A. Bjork, J. W. Froehlich, C. Lau, R. J. Singh, K. B. Wallace, and J. L. Butenhoff. 2008. “Thyroid hormone status and pituitary function in adult rats given oral doses of perfluorooctanesulfonate (PFOS).” Toxicology 243 (3):330-9. https://doi.org/10.1016/j.tox.2007.10.014.

Chapman, S. W., and B. L. Parker. 2005. “Plume persistence due to aquitard back diffusion following dense nonaqueous phase liquid source removal or isolation.” Water Resources Research 41:W12411. https://doi.org/10.1029/2005WR004224.

Chappells, Heather, Louise Parker, Conrad Fernandez, Cathy Conrad, John Drage, Gary O’Toole, Norma Campbell, and Trevor J.B. Dummer. 2014. “Arsenic in private drinking water wells: An assessment of jurisdictional regulations and guidelines for risk remediation in North America.” Journal of Water & Health 12:372-392. https://doi.org/10.2166/wh.2014.054.

Charbonnet, Joseph A., Carrie A. McDonough, Feng Xiao, Trever Schwichtenberg, Dunping Cao, Sarit Kaserzon, Kevin V. Thomas, Pradeep Dewapriya, Benjamin J. Place, Emma L. Schymanski, Jennifer A. Field, Damian E. Helbling, and Christopher P. Higgins. 2022. “Communicating Confidence of Per- and Polyfluoroalkyl Substance Identification via High-Resolution Mass Spectrometry.” Environmental Science & Technology Letters 9 (6):473-481. 10.1021/acs.estlett.2c00206.

Charbonnet, Joseph A., Alix E. Rodowa, Nayantara T. Joseph, Jennifer L. Guelfo, Jennifer A. Field, Gerrad D. Jones, Christopher P. Higgins, Damian E. Helbling, and Erika F. Houtz. 2021. “Environmental Source Tracking of Per- and Polyfluoroalkyl Substances within a Forensic Context: Current and Future Techniques.” Environmental Science & Technology 55 (11):7237-7245. https://doi.org/10.1021/acs.est.0c08506.

Chemours. 2017. “History of Teflon.” https://www.teflon.com/en/news-events/history.

Chemours. 2020. Chemours’ Thermal Oxidizer Destroying PFAS at Greater than 99.99% Efficiency. https://www.chemours.com/es/-/media/files/corporate/fayetteville-works/2020-0320-thermal-oxidizer-efficiency-results-announced.pdf.

Chemours. 2023. “Consent Order Compliance.” Chemours, Last Modified April 26, 2023. accessed 2023. https://www.chemours.com/en/about-chemours/global-reach/fayetteville-works/compliance-testing.

Chen, Fangfang, Zhiyuan Gong, and Barry C. Kelly. 2016. “Bioavailability and bioconcentration potential of perfluoroalkyl-phosphinic and -phosphonic acids in zebrafish (Danio rerio): Comparison to perfluorocarboxylates and perfluorosulfonates.” Science of The Total Environment 568:33-41. https://doi.org/10.1016/j.scitotenv.2016.05.215.

Chen, Fangfang, Shanshan Yin, Barry C. Kelly, and Weiping Liu. 2017. “Chlorinated Polyfluoroalkyl Ether Sulfonic Acids in

Matched Maternal, Cord, and Placenta Samples: A Study of Transplacental Transfer." Environmental Science & Technology 51 (11):6387-6394. https://doi.org/10.1021/acs.est.6b06049.

Chen, Hong, Shuo Chen, Xie Quan, Yazhi Zhao, and Huimin Zhao. 2009. "Sorption of perfluorooctane sulfonate (PFOS) on oil and oil-derived black carbon: Influence of solution pH and [Ca2+]." Chemosphere 77 (10):1406-1411. https://doi.org/10.1016/j.chemosphere.2009.09.008.

Chen, H., M. Reinhard, V. T. Nguyen, and K. Y.-H. Gin. 2016. "Reversible and irreversible sorption of perfluorinated compounds (PFCs) by sediments of an urban reservoir." Chemosphere 144:1747-1753. https://doi.org/10.1016/j.chemosphere.2015.10.055.

Chen, Huiting, Martin Reinhard, Tingru Yin, Tung Viet Nguyen, Ngoc Han Tran, and Karina Yew-Hoong Gin. 2019. "Multi-compartment distribution of perfluoroalkyl and polyfluoroalkyl substances (PFASs) in an urban catchment system." Water Research 154:227-237. https://doi.org/10.1016/j.watres.2019.02.009.

Chen, Hao, Lu Zhang, Mengqi Li, Yiming Yao, Zhen Zhao, Gabriel Munoz, and Hongwen Sun. 2019. "Per- and polyfluoroalkyl substances (PFASs) in precipitation from mainland China: Contributions of unknown precursors and short-chain (C2C3) perfluoroalkyl carboxylic acids." Water Research 153:169-177. https://doi.org/10.1016/j.watres.2019.01.019.

Chen, J., P. Y. Zhang, and J. Liu. 2006. "Photodegradation of perfluorooctanoic acid by 185 nm vacuum ultraviolet light." Journal of Environmental Sciences (China) 19.

Chen, Jiamiao, Hongyuan Li, Jingzhi Yao, Hua Guo, Hongxia Zhang, Yong Guo, Nan Sheng, Jianshe Wang, and Jiayin Dai. 2021. "Chronic exposure to PFO4DA and PFO5DoDA, two perfluoroalkyl ether carboxylic acids (PFECAs), suppresses hepatic stress signals and disturbs glucose and lipid metabolism in male mice." Journal of Hazardous Materials 411:124963. https://doi.org/10.1016/j.jhazmat.2020.124963.

Chen, J., and P. Zhang. 2006. "Photodegradation of perfluorooctanoic acid in water under irradiation of 254 nm and 185 nm light by use of persulfate." Water Science & Technology 54 (11-12):317-325. https://doi.org/10.2166/wst.2006.731.

Chen, Jing, Peng-yi Zhang, and Jian Liu. 2007. "Photodegradation of perfluorooctanoic acid by 185 nm vacuum ultraviolet light." Journal of Environmental Sciences 19 (4):387-390. https://doi.org/10.1016/S1001-0742(07)60064-3.

Chen, Li D., Chun-Ze Lai, Laura P. Granda, Melissa A. Fierke, Debaprasad Mandal, Andreas Stein, John A. Gladysz, and Philippe Bühlmann. 2013. "Fluorous Membrane Ion-Selective Electrodes for Perfluorinated Surfactants: Trace-Level Detection and in Situ Monitoring of Adsorption." Analytical Chemistry 85 (15):7471-7477. https://doi.org/10.1021/ac401424j.

Chen, Qiaoying, Shujun Yi, Qingqing Ye, Yumin Zhu, Wenjue Zhong, and Lingyan Zhu. 2022. "Insights into the Dermal Absorption, Deposition, and Elimination of Poly- and Perfluoroalkyl Substances in Rats: The Importance of Skin Exposure." Environmental Science & Technology 56 (23):16975-16984. 10.1021/acs.est.2c03181.

Chen, Shu, Xing-Chun Jiao, Nan Gai, Xiao-Jie Li, Xiao-Chun Wang, Guo-Hui Lu, Hai-Tao Piao, Zhu Rao, and Yong-Liang Yang. 2016. "Perfluorinated compounds in soil, surface water, and groundwater from rural areas in eastern China." Environmental Pollution 211:124-131. https://doi.org/10.1016/j.envpol.2015.12.024.

Chen, Shuqin, Yunqiao Zhou, Jing Meng, and Tieyu Wang. 2018. "Seasonal and annual variations in removal efficiency of perfluoroalkyl substances by different wastewater treatment processes." Environmental Pollution 242:2059-2067. https://doi.org/10.1016/j.envpol.2018.06.078.

Chen, Shuqin, Yunqiao Zhou, Jing Meng, and Tieyu Wang. 2018. "Seasonal and annual variations in removal efficiency of perfluoroalkyl substances by different wastewater treatment processes." Environmental Pollution 242:2059-2067. https://doi.org/10.1016/j.envpol.2018.06.078.

Chen, Tian, Ling Zhang, Jun-qiu Yue, Zi-quan Lv, Wei Xia, Yan-jian Wan, Yuan-yuan Li, and Shun-qing Xu. 2012. "Prenatal PFOS exposure induces oxidative stress and apoptosis in the lung of rat off-spring." Reproductive Toxicology 33 (4):538-545. https://doi.org/10.1016/j.reprotox.2011.03.003.

Chen, Xi, Xinghui Xia, Xilong Wang, Jinping Qiao, and Huiting Chen. 2011. “A comparative study on sorption of perfluorooctane sulfonate (PFOS) by chars, ash and carbon nanotubes.” Chemosphere 83 (10):1313-1319. https://doi.org/10.1016/j.chemosphere.2011.04.018.

Chen, Ying-Chin, Shang-Lien Lo, and Yu-Chi Lee. 2012. “Distribution and fate of perfluorinated compounds (PFCs) in a pilot constructed wetland.” Desalination and Water Treatment 37 (1-3):178-184. https://doi.org/10.1080/19443994.2012.661270.

Chen, Yan-Min, and Liang-Hong Guo. 2009. “Fluorescence study on site-specific binding of perfluoroalkyl acids to human serum albumin.” Archives of Toxicology 83 (3):255. https://doi.org/10.1007/s00204-008-0359-x.

Cheng, Jie, Chad D. Vecitis, Hyunwoong Park, Brian T. Mader, and Michael R. Hoffmann. 2008. “Sonochemical Degradation of Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoate (PFOA) in Landfill Groundwater: Environmental Matrix Effects.” Environmental Science & Technology 42 (21):8057-8063. https://doi.org/10.1021/es8013858.

Cheng, Jie, Chad D. Vecitis, Hyunwoong Park, Brian T. Mader, and Michael R. Hoffmann. 2010. “Sonochemical Degradation of Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoate (PFOA) in Groundwater: Kinetic Effects of Matrix Inorganics.” Environmental Science & Technology 44 (1):445-450. https://doi.org/10.1021/es902651g.

Cheng, Jian-hua, Xiao-yan Liang, She-wei Yang, and Yong-you Hu. 2014. “Photochemical defluorination of aqueous perfluorooctanoic acid (PFOA) by VUV/Fe3+ system.” Chemical Engineering Journal 239:242-249. https://doi.org/10.1016/j.cej.2013.11.023.

Cheng, Weixiao, and Carla A. Ng. 2019. “Using Machine Learning to Classify Bioactivity for 3486 Per- and Polyfluoroalkyl Substances (PFASs) from the OECD List.” Environmental Science & Technology 53 (23):13970-13980. https://doi.org/10.1021/acs.est.9b04833.

Cheng, Yan, Yuan Cui, Hui-ming Chen, and Wen-ping Xie. 2011. “Thyroid disruption effects of environmental level perfluorooctane sulfonates (PFOS) in Xenopus laevis.” Ecotoxicology 20 (8):2069-2078. 10.1007/s10646-011-0749-3.

Cheng, Yu H., Dushyant Barpaga, Jennifer A. Soltis, V. Shutthanandan, Roli Kargupta, Kee Sung Han, B. Peter McGrail, Radha Kishan Motkuri, Sagnik Basuray, and Sayandev Chatterjee. 2020. “Metal–Organic Framework-Based Microfluidic Impedance Sensor Platform for Ultrasensitive Detection of Perfluorooctanesulfonate.” ACS Applied Materials & Interfaces 12 (9):10503-10514. https://doi.org/10.1021/acsami.9b22445.

Chengelis, C. P., J. B. Kirkpatrick, N. R. Myers, M. Shinohara, P. L. Stetson, and D. W. Sved. 2009. “Comparison of the toxicokinetic behavior of perfluorohexanoic acid (PFHxA) and nonafluorobutane-1-sulfonic acid (PFBS) in cynomolgus monkeys and rats.” Reprod Toxicol 27 (3-4):400-406. https://doi.org/10.1016/j.reprotox.2009.01.013.

Chengelis, C. P., J. B. Kirkpatrick, A. Radovsky, and M. Shinohara. 2009. “A 90-day repeated dose oral (gavage) toxicity study of perfluorohexanoic acid (PFHxA) in rats (with functional observational battery and motor activity determinations).” Reprod Toxicol 27 (3-4):342-351. https://doi.org/10.1016/j.reprotox.2009.01.006.

Chiang, D., S. Laing, R. Casson, R. Mora, and Q. Huang. 2018. “Applications of Electrochemical Oxidation for PFAS Destruction in Water, Liquid and Solid Wastes.” Battelle Conference, Palm Springs, CA.

Chiang, D., R. Stewart, G. Birk, Q. Huang, J. Field, and Bodour A. 2017. “Ability of Aluminum-Based Adsorbent to Remove PFAS from Groundwater.” Battelle Conference, Palm Springs, CA.

Choe, Jong Kwon, Allison M. Bergquist, Sangjo Jeong, Jeremy S. Guest, Charles J. Werth, and Timothy J. Strathmann. 2015. “Performance and life cycle environmental benefits of recycling spent ion exchange brines by catalytic treatment of nitrate.” Water Research 80:267-280. https://doi.org/10.1016/j.watres.2015.05.007.

Choe, Jong Kwon, Michelle H. Mehnert, Jeremy S. Guest, Timothy J. Strathmann, and Charles J. Werth. 2013. “Comparative Assessment of the Environmental Sustainability of Existing and Emerging Perchlorate Treatment Technologies for Drinking Water.” Environmental Science & Technology 47 (9):4644-4652. https://doi.org/10.1021/es3042862.

Choi, Dae-Geun, Jun-Ho Jeong, Young-suk Sim, Eung-sug Lee, Woo Soo Kim, and Byeong-Soo Bae. 2005. “Fluorinated

Organic−Inorganic Hybrid Mold as a New Stamp for Nanoimprint and Soft Lithography." Langmuir: the ACS journal of surfaces and colloids 21 (21):9390-9392. https://doi.org/10.1021/la0513205.

Choi, Youn Jeong, Damian E. Helbling, Jinxia Liu, Christopher I. Olivares, and Christopher P. Higgins. 2022. "Microbial biotransformation of aqueous film-forming foam derived polyfluoroalkyl substances." Science of The Total Environment 824:153711. https://doi.org/10.1016/j.scitotenv.2022.153711.

Choi, Youn Jeong, Rooney Kim Lazcano, Peyman Yousefi, Heather Trim, and Linda S. Lee. 2019. "Perfluoroalkyl Acid Characterization in U.S. Municipal Organic Solid Waste Composts." Environmental Science & Technology Letters 6 (6):372-377. 10.1021/acs.estlett.9b00280.

Chowdhury, Pankaj, and T. Viraraghavan. 2009. "Sonochemical degradation of chlorinated organic compounds, phenolic compounds and organic dyes – A review." Science of The Total Environment 407 (8):2474-2492. https://doi.org/10.1016/j.scitotenv.2008.12.031.

Christopher, K. Ober, Kafer Florian, and Deng Jingyuan. 2022. "Review of essential use of fluorochemicals in lithographic patterning and semiconductor processing." Journal of Micro/Nanopatterning, Materials, and Metrology 21 (1):010901. 10.1117/1.JMM.21.1.010901.

Chu, Shaogang, Robert J. Letcher, Daryl J. McGoldrick, and Sean M. Backus. 2016. "A New Fluorinated Surfactant Contaminant in Biota: Perfluorobutane Sulfonamide in Several Fish Species." Environmental Science & Technology 50 (2):669-675. 10.1021/acs.est.5b05058.

City of Portsmouth. 2022. Technical Memorandum Evaluation of PFAS in Synthetic Turf, City of Portsmouth, NH. https://www.cityofportsmouth.com/recreation/other-reports-documents.

Clara, M., S. Scharf, S. Weiss, O. Gans, and C. Scheffknecht. 2008. "Emissions of perfluorinated alkylated substances (PFAS) from point sources – Identification of relevant branches." Water Science & Technology 58 (1):59-66. https://doi.org/10.2166/wst.2008.641.

Clarke, Bradley O., and Stephen R. Smith. 2011. "Review of 'emerging' organic contaminants in biosolids and assessment of international research priorities for the agricultural use of biosolids." Environment International 37 (1):226-247. https://doi.org/10.1016/j.envint.2010.06.004.

Cleland, Marshall R. 2011. "Electron Bean Materials Irradiators." In Industrial Accelerators and Their Applications, edited by R.W. Hamm and M.E. Hamm, 87-137. World Scientific. ISBN No. 978-981-4307-04-8.

Code of Federal Regulations 14. 2012. Certification of Airports, Section 317 Aircraft rescue and firefighting: Equipment and agents. https://www.gpo.gov/fdsys/pkg/CFR-10821 2012-title14-vol3/xml/CFR-2012-title14-vol3-part139.xml

Code of Federal Regulations 40. 2008. Criteria for Municipal Solid Waste Landfills, Section 258.40 Design criteria. https://www.gpo.gov/fdsys/pkg/CFR-2008-title40-10824 vol24/xml/CFR-2008-title40-vol24-sec258-40.xml.

Codling, Garry, Crispin Halsall, Lutz Ahrens, Sabino Del Vento, Karin Wiberg, Magnus Bergknut, Hjalmar Laudon, and Ralf Ebinghaus. 2014. "The fate of per- and polyfluoroalkyl substances within a melting snowpack of a boreal forest." Environmental Pollution 191:190-198. https://doi.org/10.1016/j.envpol.2014.04.032.

Codling, Garry, Neil C. Sturchio, Karl Rockne, An Li, H. Peng, Timothy Tse, Paul Jones, and John P. Giesy. 2018. "Spatial and temporal trends in poly- and per-fluorinated compounds in the Laurentian Great Lakes Erie, Ontario and St. Clair." Environmental Pollution 237:396-405. https://doi.org/10.1016/j.envpol.2018.02.013.

Colgan, G., R. Richter, R. Grace, T. Fitzpatrick, R. Darlington, B. DiGuiseppi, L. Cook, and K. Rabe. 2018. "Thermal Treatment of Per- and Polyfluoroalkyl Substances (PFAS) in Soil." Battelle Chlorinated Conference, Palm Springs, California.

CONCAWE. 2016. Environmental Fate and Effects of Poly- and Perfluoroalkyl Substances (PFAS). Auderghem, Belgium. https://www.concawe.eu/publication/environmental-fate-and-effects-of-poly-and-perfluoroalkyl-substances-pfas-report-no-816/.

Conder, J., J. Arblaster, E. Larson, J. Brown, and C. Higgins. 2020. Guidance for Assessing the Ecological Risks of PFAS to

Threatened and Endangered Species at Aqueous Film Forming Foam-Impacted Sites. SERDP Project ER 18-1614. Alexandria, VA: Strategic Environmental Research and Development Program. https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/ER18-1614/(language)/eng-US.

Conder, Jason M., Robert A. Hoke, Watze de Wolf, Mark H. Russell, and Robert C. Buck. 2008. “Are PFCAs Bioaccumulative? A Critical Review and Comparison with Regulatory Criteria and Persistent Lipophilic Compounds.” Environmental Science & Technology 42 (4):995-1003. https://doi.org/10.1021/es070895g.

Conley, Justin M., Christy S. Lambright, Nicola Evans, Elizabeth Medlock-Kakaley, Aaron Dixon, Donna Hill, James McCord, Mark J. Strynar, Jermaine Ford, and L. Earl Gray. 2022. “Cumulative maternal and neonatal effects of combined exposure to a mixture of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) during pregnancy in the Sprague-Dawley rat.” Environment international 170:107631. 10.1016/j.envint.2022.107631.

Conley, Justin M., Christy S. Lambright, Nicola Evans, Elizabeth Medlock-Kakaley, Donna Hill, James McCord, Mark J. Strynar, Leah C. Wehmas, Susan Hester, Denise K. MacMillan, and L. Earl Gray. 2022. “Developmental toxicity of Nafion byproduct 2 (NBP2) in the Sprague-Dawley rat with comparisons to hexafluoropropylene oxide-dimer acid (HFPO-DA or GenX) and perfluorooctane sulfonate (PFOS).” Environment International 160:107056. https://doi.org/10.1016/j.envint.2021.107056.

Conley Justin, M., S. Lambright Christy, Nicola Evans, J. Strynar Mark, James McCord, S. McIntyre Barry, S. Travlos Gregory, C. Cardon Mary, Elizabeth Medlock-Kakaley, C. Hartig Phillip, S. Wilson Vickie, and L. Earl Gray. 2019. “Adverse Maternal, Fetal, and Postnatal Effects of Hexafluoropropylene Oxide Dimer Acid (GenX) from Oral Gestational Exposure in Sprague-Dawley Rats.” Environmental Health Perspectives 127 (3):037008. https://doi.org/10.1289/EHP4372.

Conte, L., L. Falletti, A. Zaggia, and M. Milan. 2015. “Polyfluorinated Organic Micropollutants Removal from Water by Ion Exchange and Adsorption.” Chemical Engineering Transactions 43:2257-2262. https://doi.org/10.3303/CET1543377.

Coperchini, F., O. Awwad, M. Rotondi, F. Santini, M. Imbriani, and L. Chiovato. 2017. “Thyroid disruption by perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA).” J Endocrinol Invest 40 (2):105-121. https://doi.org/10.1007/s40618-016-0572-z.

Corton, J. C., S. P. Anderson, and A. Stauber. 2000. “Central role of peroxisome proliferator-activated receptors in the actions of peroxisome proliferators.” Annu Rev Pharmacol Toxicol 40:491-518. https://doi.org/10.1146/annurev.pharmtox.40.1.491.

Costanza, Jed, Linda M. Abriola, and Kurt D. Pennell. 2020. “Aqueous Film-Forming Foams Exhibit Greater Interfacial Activity than PFOA, PFOS, or FOSA.” Environmental Science & Technology 54 (21):13590-13597. https://doi.org/10.1021/acs.est.0c03117.

Costanza, Jed, Masoud Arshadi, Linda M. Abriola, and Kurt D. Pennell. 2019. “Accumulation of PFOA and PFOS at the Air–Water Interface.” Environmental Science & Technology Letters 6 (8):487-491. https://doi.org/10.1021/acs.estlett.9b00355.

Costello, M. Christina Schilling, and Linda S. Lee. 2020. “Sources, Fate, and Plant Uptake in Agricultural Systems of Per- and Polyfluoroalkyl Substances.” Current Pollution Reports. https://10.1007/s40726-020-00168-y.

Council of Australian Governments. 2018. Intergovernmental Agreement on a National Framework for Responding to PFAS Contamination, Appendix C: PFAS Information sharing, Communication, and Engagement Guidelines.

Cousins, Ian T., Jamie C. De Witt, Juliane Glüge, Gretta Goldenman, Dorte Herzke, Rainer Lohmann, Mark Miller, Carla A. Ng, Sharyle Patton, Martin Scheringer, Xenia Trier, and Zhanyun Wang. 2021. “Finding essentiality feasible: common questions and misinterpretations concerning the “essential-use” concept.” Environmental Science: Processes & Impacts 23 (8):1079-1087. 10.1039/D1EM00180A.

Cousins, Ian T., Jamie C. DeWitt, Juliane Glüge, Gretta Goldenman, Dorte Herzke, Rainer Lohmann, Mark Miller, Carla A. Ng, Martin Scheringer, Lena Vierke, and Zhanyun Wang. 2020. “Strategies for grouping per- and polyfluoroalkyl substances (PFAS) to protect human and environmental health.” Environmental Science: Processes & Impacts 22 (7):1444-1460. https://doi.org/10.1039/D0EM00147C.

Cousins, Ian T., Jamie C. DeWitt, Juliane Glüge, Gretta Goldenman, Dorte Herzke, Rainer Lohmann, Carla A. Ng, Martin Scheringer, and Zhanyun Wang. 2020. "The high persistence of PFAS is sufficient for their management as a chemical class." Environmental Science: Processes & Impacts 22 (12):2307-2312. 10.1039/D0EM00355G.

Cousins, Ian T., Gretta Goldenman, Dorte Herzke, Rainer Lohmann, Mark Miller, Carla A. Ng, Sharyle Patton, Martin Scheringer, Xenia Trier, Lena Vierke, Zhanyun Wang, and Jamie C. DeWitt. 2019. "The concept of essential use for determining when uses of PFASs can be phased out." Environmental Science: Processes & Impacts 21 (11):1803-1815. 10.1039/C9EM00163H.

Cousins, Ian T., Jana H. Johansson, Matthew E. Salter, Bo Sha, and Martin Scheringer. 2022. "Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS)." Environmental Science & Technology 56 (16):11172-11179. https://doi.org/10.1021/acs.est.2c02765.

Covello, V.T. Message Mapping. Center for Risk Communication. https://centerforriskcommunication.org.

Covello, V.T., and F. Allen. 1988. Seven Cardinal Rules of Risk Communication. Washington, D.C.: US Environmental Protection Agency Office of Policy Analysis.

Covello, V.T., S. K. Minamyer, and K. Clayton. 2007. Effective Risk and Crisis Communication During Water Security Emergencies: Report of EPA Sponsored Message Mapping Workshops. EPA/600/R-07/027. Washington, D.C.: U.S. Environmental Protection Agency.

Covello, Vincent T., Richard G. Peters, Joseph G. Wojtecki, and Richard C. Hyde. 2001. "Risk communication, the West Nile virus epidemic, and bioterrorism: responding to the communication challenges posed by the intentional or unintentional release of a pathogen in an urban setting." Journal of Urban Health 78 (2):382-391. https://doi.org/10.1093/jurban/78.2.382.

Covello, Vincent T., Richard G. Peters, Joseph G. Wojtecki, and Richard C. Hyde. 2001. "Risk communication, the West Nile virus epidemic, and bioterrorism: responding to the commnication challenges posed by the intentional or unintentional release of a pathogen in an urban setting." Journal of Urban Health 78 (2):382-391. 10.1093/jurban/78.2.382.

CRC CARE. 2016. A human health review of PFOS and PFOA. CRC CARE Technical Report No. 42. Newcastle, Australia: CRC for Contamination Assessment and Remediation of the Environment. https://www.crccare.com/publications/technical-reports/technical-reports.

CRC CARE. 2017. Assessment, Management and Remediation Guidance for Perfluorooctanesulfonate (PFOS) and Perfluorooctanoic Acid (PFOA) – Part 5: Management and Remediation of PFOS and PFOA CRC CARE Technical Report No. 38. Newcastle, Australia: CRC for Contamination Assessment and Remediation of the Environment. https://www.crccare.com/.

CRC CARE. 2017. Assessment, Management and Remediation Guidance for Perfluorooctanesulfonate (PFOS) and Perfluorooctanoic Acid (PFOA) – Part 3: ecological screening levels. CRC CARE Technical Report No. 38. Newcastle, Australia: CRC for Contamination Assessment and Remediation of the Environment. https://www.crccare.com/.

CRC CARE. 2018. Practitioner guide to risk-based assessment, remediation and management of PFAS site contamination. Newcastle, Australia: CRC for Contamination Assessment and Remediation of the Environment. https://www.crccare.com/publications/technical-reports.

Crownover, Emily, Daniel Oberle, Mark Kluger, and Gorm Heron. 2019. "Perfluoroalkyl and polyfluoroalkyl substances thermal desorption evaluation." Remediation Journal 29 (4):77-81. https://doi.org/10.1002/rem.21623.

CSWAB. 2018. Community Priorities and Objectives for Test Methods and Remedies at Known and Potential PFAS Sites.

CT DEP. 2010. Site Characterization Guidance Document. Connecticut Department of Environmental Protection.

CT DPH. 2016. Drinking Water Action Level for Perfluorinated Alkyl Substances (PFAS). https://portal.ct.gov/-/media/Departments-and-Agencies/DPH/dph/environmental_health/eoha/Toxicology_Risk_Assessment/DrinkingWaterActionLevelPerfluorinatedAlkylSubstances-PFAS.pdf?la=e.

CT DPH. 2022. Summary Data on PFAS in Artificial Turf for PFAS.

CTDEEP. 2022. State of Connecticut AFFF Take-Back Program: Draining and Rinsing AFFF from Municipal Onboard Systems. https://portal.ct.gov/-/media/CFPC/KO/2022/Latest-News/Muni-FD-AFFF-drain-rinse-SOP-FINAL-2022-05-18.pdf.

CTDEEP. 2022. Connecticut’s Program to Evaluate AFFF Alternatives and Equipment Decontamination. https://portal.ct.gov/-/media/DEEP/site_clean_up/contaminants_of_emerging_concern/PFAS_documents/BizNGO-AFFF-Transitioning-in-CT-SPociu-2022-12-05-DRAFT.pdf.

Cui, Junkui, Panpan Gao, and Yang Deng. 2020. “Destruction of Per- and Polyfluoroalkyl Substances (PFAS) with Advanced Reduction Processes (ARPs): A Critical Review.” Environmental Science & Technology 54 (7):3752-3766. 10.1021/acs.est.9b05565.

Cui, L., Q. F. Zhou, C. Y. Liao, J. J. Fu, and G. B. Jiang. 2009. “Studies on the toxicological effects of PFOA and PFOS on rats using histological observation and chemical analysis.” Arch Environ Contam Toxicol 56 (2):338-49. https://doi.org/10.1007/s00244-008-9194-6.

Cui, L., Q. F. Zhou, C. Y. Liao, J. J. Fu, and G. B. Jiang. 2009. “Studies on the toxicological effects of PFOA and PFOS on rats using histological observation and chemical analysis.” Arch Environ Contam Toxicol 56 (2):338-49. https://doi.org/10.1007/s00244-008-9194-6.

Cummings, L., A. Matarazzo, N. Nelson, F. Sickels, and C.T. Storms. 2015. New Jersey Drinking Water Quality Institute Subcommittee, Recommendation on Perfluorinated Compound Treatment Options for Drinking Water. New Jersey Department of Environmental Protection.

Cundy, A. B., R. P. Bardos, A. Church, M. Puschenreiter, W. Friesl-Hanl, I. Müller, S. Neu, M. Mench, N. Witters, and J. Vangronsveld. 2013. “Developing principles of sustainability and stakeholder engagement for “gentle” remediation approaches: The European context.” Journal of Environmental Management 129:283-291. https://doi.org/10.1016/j.jenvman.2013.07.032.

Curran, I., S. L. Hierlihy, V. Liston, P. Pantazopoulos, A. Nunnikhoven, S. Tittlemier, M. Barker, K. Trick, and G. Bondy. 2008. “Altered fatty acid homeostasis and related toxicologic sequelae in rats exposed to dietary potassium perfluorooctanesulfonate (PFOS).” J Toxicol Environ Health A 71 (23):1526-41. https://doi.org/10.1080/15287390802361763.

Custer, Christine M. 2021. “Linking field and laboratory studies: Reproductive effects of perfluorinated substances on avian populations.” Integrated Environmental Assessment and Management 17 (4):690-696. https://doi.org/10.1002/ieam.4394.

Custer, Christine M., Thomas W. Custer, Robert Delaney, Paul M. Dummer, Sandra Schultz, and Natalie Karouna-Renier. 2019. “Perfluoroalkyl Contaminant Exposure and Effects in Tree Swallows Nesting at Clarks Marsh, Oscoda, Michigan, USA.” Archives of Environmental Contamination and Toxicology 77 (1):1-13. https://doi.org/10.1007/s00244-019-00620-1.

Custer, Christine M., Thomas W. Custer, Paul M. Dummer, Matthew A. Etterson, Wayne E. Thogmartin, Qian Wu, Kurunthachalam Kannan, Annette Trowbridge, and Patrick C. McKann. 2014. “Exposure and Effects of Perfluoroalkyl Substances in Tree Swallows Nesting in Minnesota and Wisconsin, USA.” Archives of Environmental Contamination and Toxicology 66 (1):120-138. https://doi.org/10.1007/s00244-013-9934-0.

Custer, Christine M., Thomas W. Custer, Heiko L. Schoenfuss, Beth H. Poganski, and Laura Solem. 2012. “Exposure and effects of perfluoroalkyl compounds on tree swallows nesting at Lake Johanna in east central Minnesota, USA.” Reproductive Toxicology 33 (4):556-562. https://doi.org/10.1016/j.reprotox.2011.01.005.

Custer, C. M., B. R. Gray, and T. W. Custer. 2010. “Effects of egg order on organic and inorganic element concentrations and egg characteristics in tree swallows, Tachycineta bicolor.” Environ Toxicol Chem 29 (4):909-21. https://doi.org/10.1002/etc.88.

D’Agostino, Lisa A., and Scott A. Mabury. 2017. “Aerobic biodegradation of 2 fluorotelomer sulfonamide–based aqueous film–forming foam components produces perfluoroalkyl carboxylates.” Environmental Toxicology and Chemistry 36

(8):2012-2021. https://doi.org/10.1002/etc.3750.

D’Eon, Jessica, and Scott A. Mabury. 2007. “Production of Perfluorinated Carboxylic Acids (PFCAs) from the Biotransformation of Polyfluoroalkyl Phosphate Surfactants (PAPS): Exploring Routes of Human Contamination.” Environmental science & technology 41:4799-805. https://doi.org/10.1021/es070126x.

D’Eon, Jessica, and Scott A. Mabury. 2011. “Exploring Indirect Sources of Human Exposure to Perfluoroalkyl Carboxylates (PFCAs): Evaluating Uptake, Elimination, and Biotransformation of Polyfluoroalkyl Phosphate Esters (PAPs) in the Rat.” Environ Health Perspectives 119 (3):344-50. https://doi.org/10.1289/ehp.1002409.

D’Eon, Jessica C., Michael D. Hurley, Timothy J. Wallington, and Scott A. Mabury. 2006. “Atmospheric Chemistry of N-methyl Perfluorobutane Sulfonamidoethanol, C4F9SO2N(CH3)CH2CH2OH: Kinetics and Mechanism of Reaction with OH.” Environmental Science & Technology 40 (6):1862-1868. https://doi.org/10.1021/es0520767.

D’Agostino, Lisa A., and Scott A. Mabury. 2014. “Identification of Novel Fluorinated Surfactants in Aqueous Film Forming Foams and Commercial Surfactant Concentrates.” Environmental Science & Technology 48 (1):121-129. 10.1021/es403729e.

D’Ambro, Emma L., Havala O. T. Pye, Jesse O. Bash, James Bowyer, Chris Allen, Christos Efstathiou, Robert C. Gilliam, Lara Reynolds, Kevin Talgo, and Benjamin N. Murphy. 2021. “Characterizing the Air Emissions, Transport, and Deposition of Per- and Polyfluoroalkyl Substances from a Fluoropolymer Manufacturing Facility.” Environmental Science & Technology 55 (2):862-870. 10.1021/acs.est.0c06580.

D’Eon, Jessica C., and Scott A. Mabury. 2011. “Is Indirect Exposure a Significant Contributor to the Burden of Perfluorinated Acids Observed in Humans?” Environmental Science & Technology 45 (19):7974-7984. https://doi.org/10.1021/es200171y.

Da Silva, B. F., J. J. Aristtizabal-Henao, J. Aufmuth, J. Awkerman, and J. A. Bowden. 2022. “Survey of per- and polyfluoroalkyl substances (PFAS) in surface water collected in Pensacola, FL.” Heliyon 8 (8). https://doi.org/10.1016/j.heliyon.2022.e10239.

da Silva-Rackov, C.K., W.A. Lawal, P.A. Nfodzo, M.M. Vianna, C.A. do Nascimento, and H. Choi. 2016. “Degradation of PFOA by hydrogen peroxide and persulfate activated by iron-modified diatomite.” Applied Catalysis B: Environmental 192:253-259. https://doi.org/10.1016/j.apcatb.2016.03.067.

Dai, Xiaodong, Zongli Xie, Brian Dorian, Stephen Gray, and Jianhua Zhang. 2019. “Comparative study of PFAS treatment by UV, UV/ozone, and fractionations with air and ozonated air.” Environmental Science: Water Research & Technology 5 (11):1897-1907. 10.1039/C9EW00701F.

Dai, Xiaodong, Zongli Xie, Brian Dorian, Stephen Gray, and Jianhua Zhang. 2019. “Comparative study of PFAS treatment by UV, UV/ozone, and fractionations with air and ozonated air.” Environmental Science: Water Research & Technology 5 (11):1897-1907. 10.1039/C9EW00701F.

Dai, Zhineng, Xinghui Xia, Jia Guo, and Xiaoman Jiang. 2013. “Bioaccumulation and uptake routes of perfluoroalkyl acids in Daphnia magna.” Chemosphere 90 (5):1589-1596. https://doi.org/10.1016/j.chemosphere.2012.08.026.

Dalahmeh, Sahar, Sana Tirgani, Allan John Komakech, Charles B. Niwagaba, and Lutz Ahrens. 2018. “Per- and polyfluoroalkyl substances (PFASs) in water, soil and plants in wetlands and agricultural areas in Kampala, Uganda.” Science of The Total Environment 631-632:660-667. https://doi.org/10.1016/j.scitotenv.2018.03.024.

Danish EPA. 2015. Alternatives to Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) in Textiles. Copenhagen. http://www2.mst.dk/Udgiv/publications/2015/05/978-87-93352-16-2.pdf.

Danish EPA. 2015. Perfluoroalkylated substances: PFOA, PFOS and PFOSA, Evaluation of health hazards and proposal of a health-based quality criterion for drinking water, soil and ground water. Environmental project No. 1665. https://www2.mst.dk/Udgiv/publications/2015/04/978-87-93283-01-5.pdf

Danish EPA. 2015. Short-chain Polyfluoroalkyl Substances (PFAS). A literature review of information on human health effects and environmental fate and effect aspects of short-chain PFAS. Environmental project No. 1707. https://www2.mst.dk/Udgiv/publications/2015/05/978-87-93352-15-5.pdf

Danish EPA. 2022. Sustainable Remediation Methodology for Assessment. Environmental Project No. 2209 (pp. 36-48): Ministry of Environment of Denmark. https://www2.mst.dk/Udgiv/publications/2022/08/978-87-7038-435-3.pdf.

Danish Ministry of the Environment. 2015. Short-chain Polyfluoroalkyl Substances (PFAS): A literature review of information on human health effects and environmental fate and effect aspects of short-chain PFAS. Environmental project No. 1707, 2015: The Danish Environmental Protection Agency.

Darrow, L. A., C. R. Stein, and K. Steenland. 2013. “Serum perfluorooctanoic acid and perfluorooctane sulfonate concentrations in relation to birth outcomes in the Mid-Ohio Valley, 2005-2010.” Environ Health Perspect 121 (10):1207-13. https://doi.org/10.1289/ehp.1206372.

Darwin, R. L. 2011. Estimated Inventory of PFOS-based Aqueous Film Forming Foam (AFFF). Fire Fighting Foam Coalition.

Das, K. P., B. E. Grey, M. B. Rosen, C. R. Wood, K. R. Tatum-Gibbs, R. D. Zehr, M. J. Strynar, A. B. Lindstrom, and C. Lau. 2015. “Developmental toxicity of perfluorononanoic acid in mice.” Reprod Toxicol 51:133-44. https://doi.org/10.1016/j.reprotox.2014.12.012.

Das, K. P., B. E. Grey, R. D. Zehr, C. R. Wood, J. L. Butenhoff, S. C. Chang, D. J. Ehresman, Y. M. Tan, and C. Lau. 2008. “Effects of perfluorobutyrate exposure during pregnancy in the mouse.” Toxicol Sci 105 (1):173-81. https://doi.org/10.1093/toxsci/kfn099.

Das, K. P., C. R. Wood, M. T. Lin, A. A. Starkov, C. Lau, K. B. Wallace, J. C. Corton, and B. D. Abbott. 2017. “Perfluoroalkyl acids-induced liver steatosis: Effects on genes controlling lipid homeostasis.” Toxicology 378:37-52. https://doi.org/10.1016/j.tox.2016.12.007.

Dassuncao, Clifton, Xindi C. Hu, Xianming Zhang, Rossana Bossi, Maria Dam, Bjarni Mikkelsen, and Elsie M. Sunderland. 2017. “Temporal Shifts in Poly- and Perfluoroalkyl Substances (PFASs) in North Atlantic Pilot Whales Indicate Large Contribution of Atmospheric Precursors.” Environmental Science & Technology 51 (8):4512-4521. https://doi.org/10.1021/acs.est.7b00293.

Dassuncao, Clifton, Heidi Pickard, Marisa Pfohl, Andrea K. Tokranov, Miling Li, Bjarni Mikkelsen, Angela Slitt, and Elsie M. Sunderland. 2019. “Phospholipid Levels Predict the Tissue Distribution of Poly- and Perfluoroalkyl Substances in a Marine Mammal.” Environmental Science & Technology Letters 6 (3):119-125. https://doi.org/10.1021/acs.estlett.9b00031.

Dasu, Kavitha, and Linda S. Lee. 2016. “Aerobic biodegradation of toluene-2,4-di(8:2 fluorotelomer urethane) and hexamethylene-1,6-di(8:2 fluorotelomer urethane) monomers in soils.” Chemosphere 144:2482-2488. https://doi.org/10.1016/j.chemosphere.2015.11.021.

Dasu, Kavitha, Linda S. Lee, Ronald F. Turco, and Loring F. Nies. 2013. “Aerobic biodegradation of 8:2 fluorotelomer stearate monoester and 8:2 fluorotelomer citrate triester in forest soil.” Chemosphere 91 (3):399-405. https://doi.org/10.1016/j.chemosphere.2012.11.076.

Dasu, Kavitha, Jinxia Liu, and Linda S. Lee. 2012. “Aerobic Soil Biodegradation of 8:2 Fluorotelomer Stearate Monoester.” Environmental Science & Technology 46 (7):3831-3836. https://doi.org/10.1021/es203978g.

Dasu, Kavitha, Xiaoyan Xia, Dinusha Siriwardena, Theodore P. Klupinski, and Brannon Seay. 2022. “Concentration profiles of per- and polyfluoroalkyl substances in major sources to the environment.” Journal of Environmental Management 301:113879. https://doi.org/10.1016/j.jenvman.2021.113879.

Dauchy, Xavier, Virginie Boiteux, Cristina Bach, Adeline Colin, Jessica Hemard, Christophe Rosin, and Jean-François Munoz. 2017. “Mass flows and fate of per- and polyfluoroalkyl substances (PFASs) in the wastewater treatment plant of a fluorochemical manufacturing facility.” Science of The Total Environment 576:549-558. https://doi.org/10.1016/j.scitotenv.2016.10.130.

Davis, Katherine L., Michael D. Aucoin, Barbara S. Larsen, Mary A. Kaiser, and Andrew S. Hartten. 2007. “Transport of ammonium perfluorooctanoate in environmental media near a fluoropolymer manufacturing facility.” Chemosphere 67 (10):2011-2019. https://doi.org/10.1016/j.chemosphere.2006.11.049.

de la Torre, Adrián, Irene Navarro, Paloma Sanz, and María de los Ángeles Mártinez. 2019. “Occurrence and human exposure assessment of perfluorinated substances in house dust from three European countries." Science of The Total Environment 685:308-314. https://doi.org/10.1016/j.scitotenv.2019.05.463.

De Silva, Amila O., James M. Armitage, Thomas A. Bruton, Clifton Dassuncao, Wendy Heiger-Bernays, Xindi C. Hu, Anna Kärrman, Barry Kelly, Carla Ng, Anna Robuck, Mei Sun, Thomas F. Webster, and Elsie M. Sunderland. 2021. "PFAS Exposure Pathways for Humans and Wildlife: A Synthesis of Current Knowledge and Key Gaps in Understanding." Environmental Toxicology and Chemistry 40 (3):631-657. https://doi.org/10.1002/etc.4935.

De Silva, Amila O., James M. Armitage, Thomas A. Bruton, Clifton Dassuncao, Wendy Heiger-Bernays, Xindi C. Hu, Anna Kärrman, Barry Kelly, Carla Ng, Anna Robuck, Mei Sun, Thomas F. Webster, and Elsie M. Sunderland. 2021. "PFAS Exposure Pathways for Humans and Wildlife: A Synthesis of Current Knowledge and Key Gaps in Understanding." Environmental Toxicology and Chemistry 40 (3):631-657. https://doi.org/10.1002/etc.4935.

De Silva, A. O., J. P. Benskin, L. J. Martin, G. Arsenault, R. McCrindle, N. Riddell, J. W. Martin, and S. A. Mabury. 2009. "Disposition of perfluorinated acid isomers in Sprague-Dawley rats; part 2: subchronic dose." Environ Toxicol Chem 28 (3):555-67. https://doi.org/10.1897/08-254.1.

De Silva, Amila O., Derek C. G. Muir, and Scott A. Mabury. 2009. "Distribution of perfluorocarboxylate isomers in select samples from the north American environment." Environmental Toxicology and Chemistry 28 (9):1801-1814. https://doi.org/10.1897/08-500.1.

De Silva, Amila O., Christine Spencer, Brian F. Scott, Sean Backus, and Derek C. G. Muir. 2011. "Detection of a Cyclic Perfluorinated Acid, Perfluoroethylcyclohexane Sulfonate, in the Great Lakes of North America." Environmental Science & Technology 45 (19):8060-8066. https://doi.org/10.1021/es200135c.

de Vries, Pepijn, Diana M. E. Slijkerman, Christiaan J. A. F. Kwadijk, Michiel J. J. Kotterman, Leo Posthuma, Dick de Zwart, Albertinka J. Murk, and Edwin M. Foekema. 2017. "The toxic exposure of flamingos to per- and Polyfluoroalkyl substances (PFAS) from firefighting foam applications in Bonaire." Marine Pollution Bulletin 124 (1):102-111. https://doi.org/10.1016/j.marpolbul.2017.07.017.

Dean, W.S., H.A. Adejumo, A. Caiati, P.M. Garay, A.S. Harmata, L. Li, E.E. Rodriguez, and S. Sundar. 2020. "A Framework for Regulation of New and Existing PFAS by EPA." Journal of Science Policy & Governance 16 (1):1-14.

Death, Clare, Cameron Bell, David Champness, Charles Milne, Suzie Reichman, and Tarah Hagen. 2021. "Per- and polyfluoroalkyl substances (PFAS) in livestock and game species: A review." Science of The Total Environment 774:144795. https://doi.org/10.1016/j.scitotenv.2020.144795.

Deeb, R.A., A. Haghani, A. Eaton, and J. Chambon. 2016. "Development and Testing of an Analytical Method for Real Time Measurement of Polyfluoroalkyl and Perfluoroalkyl Substances (PFAS)." Battelle 2016 Chlorinated Conference.

Delinsky, Amy D., Mark J. Strynar, Patricia J. McCann, Jerry L. Varns, Larry McMillan, Shoji F. Nakayama, and Andrew B. Lindstrom. 2010. "Geographical Distribution of Perfluorinated Compounds in Fish from Minnesota Lakes and Rivers." Environmental Science & Technology 44 (7):2549-2554. https://doi.org/10.1021/es903777s.

Delkash, Madjid, Babak Ebrazi Bakhshayesh, and Hossein Kazemian. 2015. "Using zeolitic adsorbents to cleanup special wastewater streams: A review." Microporous and Mesoporous Materials 214:224-241. https://doi.org/10.1016/j.micromeso.2015.04.039.

Deng, Mi, Yongming Wu, Chao Xu, Yuanxiang Jin, Xiaoli He, Jinbao Wan, Xiaoling Yu, Hongmin Rao, and Wenqing Tu. 2018. "Multiple approaches to assess the effects of F-53B, a Chinese PFOS alternative, on thyroid endocrine disruption at environmentally relevant concentrations." Science of The Total Environment 624:215-224. https://doi.org/10.1016/j.scitotenv.2017.12.101.

Deng, Shubo, Qiang Yu, Jun Huang, and Gang Yu. 2010. "Removal of perfluorooctane sulfonate from wastewater by anion exchange resins: Effects of resin properties and solution chemistry." Water Research 44 (18):5188-5195. https://doi.org/10.1016/j.watres.2010.06.038.

Deng, Shubo, Qiaoying Zhang, Yao Nie, Haoran Wei, Bin Wang, Jun Huang, Gang Yu, and Baoshan Xing. 2012. "Sorption mechanisms of perfluorinated compounds on carbon nanotubes." Environmental Pollution 168:138-144. https://doi.org/10.1016/j.envpol.2012.03.048.

Deng, Shubo, Qin Zhou, Gang Yu, Jun Huang, and Qing Fan. 2011. “Removal of perfluorooctanoate from surface water by polyaluminium chloride coagulation.” Water Research 45 (4):1774-1780. https://doi.org/10.1016/j.watres.2010.11.029.

Denly, Elizabeth, Jim Occhialini, Phil Bassignani, Michael Eberle, and Nidal Rabah. 2019. “Per- and polyfluoroalkyl substances in environmental sampling products: Fact or fiction?” Remediation Journal 29 (4):65-76. https://doi.org/10.1002/rem.21614.

Dennis, Nicole M., Farzana Hossain, Seenivasan Subbiah, Adcharee Karnjanapiboonwong, Michael L. Dennis, Chris McCarthy, Christopher G. Heron, W. Andrew Jackson, Jordan P. Crago, Jennifer A. Field, Christopher J. Salice, and Todd A. Anderson. 2021. “Chronic Reproductive Toxicity Thresholds for Northern Bobwhite Quail (Colinus virginianus) Exposed to Perfluorohexanoic Acid (PFHxA) and a Mixture of Perfluorooctane Sulfonic Acid (PFOS) and PFHxA.” Environmental Toxicology and Chemistry 40 (9):2601-2614. https://doi.org/10.1002/etc.5135.

Dennis, Nicole M., Adcharee Karnjanapiboonwong, Seenivasan Subbiah, Justin N. Rewerts, Jennifer A. Field, Chris McCarthy, Christopher J. Salice, and Todd A. Anderson. 2020. “Chronic Reproductive Toxicity of Perfluorooctane Sulfonic Acid and a Simple Mixture of Perfluorooctane Sulfonic Acid and Perfluorohexane Sulfonic Acid to Northern Bobwhite Quail (Colinus virginianus).” Environmental Toxicology and Chemistry 39 (5):1101-1111. https://doi.org/10.1002/etc.4703.

Dennis, Nicole M., Seenivasan Subbiah, Adcharee Karnjanapiboonwong, Michael L. Dennis, Chris McCarthy, Christopher J. Salice, and Todd A. Anderson. 2021. “Species- and Tissue-Specific Avian Chronic Toxicity Values for Perfluorooctane Sulfonate (PFOS) and a Binary Mixture of PFOS and Perfluorohexane Sulfonate.” Environmental Toxicology and Chemistry 40 (3):899-909. https://doi.org/10.1002/etc.4937.

DeSilva, Amila O., Derek C.G. Muir, and Scott A. Mabury. 2009. “Distribution of Perfluorocarboxylate Isomers in Select Samples from the North American Environment.” Environmental Toxicology and Chemistry 28 (9):1801-1814.

deSilva, Viraj. 2019. PFAS In Landfill Leachate. https://missouriwastecontrolcoalition.wildapricot.org/resources/Documents/2019%20conference/MWCC2019%20-deSilva%20(SCS)%20-PFAS-July%2016,%202019.pdf.

Desjardins, D., C.A. Sutherland, R.L. Van Hoven, and H.O. Krueger. 2001. PFOS: A 96-hr toxicity test with the freshwater alga (Anabaena flos-aquae). EPA Docket AR226-0186: Ltd. Wildlife International, Project Number 454A-110B.

Desjardins, D., C.A. Sutherland, R. L. Van Hoven, and H. O. Krueger. 2001. PFOS: A 96-hr toxicity test with the marine diatom (Skeletonema costatum). EPA Docket AR226-1030a056: Ltd. Wildlife International, Project Number 454A-113A.

Desjardins, D., C.A. Sutherland, R. L. Van Hoven, and H. O. Krueger. 2001. PFOS: A 7-d toxicity test with duckweed (Lemna gibba G3). EPA Docket AR226-1030a054: Ltd. Project Number 454-111 Wildlife International.

DeVito, M. 2018. REACT Program for Per- and Polyfluoroalkyl Substances. NIEHS/DNTP. https://ntp.niehs.nih.gov/ntp/about_ntp/bsc/2018/june/meetingmaterials/devito20180620_508.pdf

DeVoogt, P., U. Berger, W. de Coen, W. de Wolf, E. Heimstad, M. McLachlan, S. S. van Leeuwen, and A. van Roon. 2006. Perfluorinated Organic Compounds in the European Environment. FP6-NEST-508967.

DeWitt, Jamie C., ed. 2015. Toxicological Effects of Perfluoroalkyl and Polyfluoroalkyl Substances, Molecular and Integrative Toxicology: Humana Press, Cham. ISBN No. 978-3-319-15517-3.

DeWitt, J. C., C. B. Copeland, M. J. Strynar, and R. W. Luebke. 2008. “Perfluorooctanoic acid-induced immunomodulation in adult C57BL/6J or C57BL/6N female mice.” Environ Health Perspect 116 (5):644-50. https://doi.org/10.1289/ehp.10896.

Dhingra, R., L. A. Darrow, M. Klein, A. Winquist, and K. Steenland. 2016. “Perfluorooctanoic acid exposure and natural menopause: A longitudinal study in a community cohort.” Environ Res 146:323-30. https://doi.org/10.1016/j.envres.2015.12.037.

Dhingra, R., C. Lally, L. A. Darrow, M. Klein, A. Winquist, and K. Steenland. 2016. “Perfluorooctanoic acid and chronic kidney disease: Longitudinal analysis of a Mid-Ohio Valley community." Environ Res 145:85-92. https://doi.org/10.1016/j.envres.2015.11.018.

DHS. 2010. Risk Steering Committee Risk Lexicon 2010 Edition.

Di Battista, V., R. Kerry Rowe, D. Patch, and K. Weber. 2020. "PFOA and PFOS diffusion through LLDPE and LLDPE coextruded with EVOH at 22 °C, 35 °C, and 50 °C." Waste Management 117:93-103. https://doi.org/10.1016/j.wasman.2020.07.036.

Dickenson, E., and C. Higgins. 2016. Treatment Mitigation Strategies for Poly- and Perfluorinated Chemicals. Project #4322. Denver, Colorado: Water Research Foundation.

Dickman, Rebecca A., and Diana S. Aga. 2022. "Efficient workflow for suspect screening analysis to characterize novel and legacy per- and polyfluoroalkyl substances (PFAS) in biosolids." Analytical and Bioanalytical Chemistry 414 (15):4497-4507. 10.1007/s00216-022-04088-2.

DiGuiseppi, W., R. Richter, and M. Riggle. 2019. "Low temperature desorption of per- and polyfloroalkyl substances." The Military Engineer:52-53.

Ding, Guanghui, Jing Zhang, Yihong Chen, Luyan Wang, Man Wang, Deqi Xiong, and Yeqing Sun. 2013. "Combined Effects of PFOS and PFOA on Zebrafish (Danio rerio) Embryos." Archives of Environmental Contamination and Toxicology 64 (4):668-675. 10.1007/s00244-012-9864-2.

Ding, G. H., T. Fromel, E. J. van den Brandhof, R. Baerselman, and W. J. Peijnenburg. 2012. "Acute toxicity of poly- and perfluorinated compounds to two cladocerans, Daphnia magna and Chydorus sphaericus." Environ Toxicol Chem 31 (3):605-10. https://doi.org/10.1002/etc.1713.

Dinglasan, Mary Joyce A., Yun Ye, Elizabeth A. Edwards, and Scott A. Mabury. 2004. "Fluorotelomer Alcohol Biodegradation Yields Poly- and Perfluorinated Acids." Environmental Science & Technology 38 (10):2857-2864. https://doi.org/10.1021/es0350177.

Dinglasan-Panlilio, Mary Joyce A., and Scott A. Mabury. 2006. "Significant Residual Fluorinated Alcohols Present in Various Fluorinated Materials." Environmental Science & Technology 40 (5):1447-1453. https://doi.org/10.1021/es051619+.

DiStefano, Rebecca, Tony Feliciano, Richard A. Mimna, Adam M. Redding, and John Matthis. 2022. "Thermal destruction of PFAS during full-scale reactivation of PFAS-laden granular activated carbon." Remediation Journal 32 (4):231-238. https://doi.org/10.1002/rem.21735.

Divine, C. 2020. Osorb(R) Media Use in PFAS Passive Samplers. ER20-1127. www.serdp-estcp.org.

Divine, C., M. Frenchmeyer, K. Dally, E. Osborn, P. Anderson, and J. Zodrow. 2020. Approach for Assessing PFAS Risk to Threatened and Endangered Species. SERDP Project ER18-1654. Alexandria, VA: Strategic Environmental Research and Development Program. https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/ER18-1653.

Divine, Craig, Amar Wadhawan, Vivek Pulikkal, Prashanth Khambhammettu, and Jay Erickson. 2023. "Polyfluoroalkyl substances requiring a renewed focus on groundwater-surface water interactions." Groundwater Monitoring & Remediation 43 (1):14-31. https://doi.org/10.1111/gwmr.12569.

Dixit, Fuhar, Benoit Barbeau, Shadan Ghavam Mostafavi, and Madjid Mohseni. 2019. "PFOA and PFOS removal by ion exchange for water reuse and drinking applications: role of organic matter characteristics." Environmental Science: Water Research & Technology 5 (10):1782-1795. 10.1039/C9EW00409B.

Dixit, Fuhar, Benoit Barbeau, Shadan Ghavam Mostafavi, and Madjid Mohseni. 2020. "Removal of legacy PFAS and other fluorotelomers: Optimized regeneration strategies in DOM-rich waters." Water Research 183:116098. https://doi.org/10.1016/j.watres.2020.116098.

DMEF. 2015. Proposal for Maximum Levels for Total Organic Fluorine in Paper and Cardboard Food Packaging (in Danish). Technical University of Denmark.

Dobraca, D., L. Israel, S. McNeel, R. Voss, M. Wang, R. Gajek, J. S. Park, S. Harwani, F. Barley, J. She, and R. Das. 2015.

"Biomonitoring in California firefighters: metals and perfluorinated chemicals." J Occup Environ Med 57 (1):88-97. https://doi.org/10.1097/jom.0000000000000307.

Domingo, José L., and Martí Nadal. 2017. "Per- and Polyfluoroalkyl Substances (PFASs) in Food and Human Dietary Intake: A Review of the Recent Scientific Literature." Journal of Agricultural and Food Chemistry 65 (3):533-543. https://doi.org/10.1021/acs.jafc.6b04683.

Dominguez-Ramos, Antonio, Karan Chavan, Verónica García, Guillermo Jimeno, Jonathan Albo, Kumudini V. Marathe, Ganapati D. Yadav, and Angel Irabien. 2014. "Arsenic Removal from Natural Waters by Adsorption or Ion Exchange: An Environmental Sustainability Assessment." Industrial & Engineering Chemistry Research 53 (49):18920-18927. https://doi.org/10.1021/ie4044345.

Dong, Dengpan, Samhitha Kancharla, Justin Hooper, Marina Tsianou, Dmitry Bedrov, and Paschalis Alexandridis. 2021. "Controlling the self-assembly of perfluorinated surfactants in aqueous environments." Physical Chemistry Chemical Physics 23 (16):10029-10039. 10.1039/D1CP00049G.

Dong, G. H., M. M. Liu, D. Wang, L. Zheng, Z. F. Liang, and Y. H. Jin. 2011. "Sub-chronic effect of perfluorooctanesulfonate (PFOS) on the balance of type 1 and type 2 cytokine in adult C57BL6 mice." Arch Toxicol 85 (10):1235-44. https://doi.org/10.1007/s00204-011-0661-x.

Dong, G. H., Y. H. Zhang, L. Zheng, W. Liu, Y. H. Jin, and Q. C. He. 2009. "Chronic effects of perfluorooctanesulfonate exposure on immunotoxicity in adult male C57BL/6 mice." Arch Toxicol 83 (9):805-15. https://doi.org/10.1007/s00204-009-0424-0.

Dorrance, Lydia R., Seth Kellogg, and Adam Love. 2017. "What You Should Know About Per- and Polyfluoroalkyl Substances (PFAS) for Environmental Claims." Environmental Claims Journal 29:1-15. https://doi.org/10.1080/10406026.2017.1377015.

Downer, Adrian, Julian Eastoe, Alan R. Pitt, Jeff Penfold, and Richard K. Heenan. 1999. "Adsorption and micellisation of partially- and fully-fluorinated surfactants." Colloids and Surfaces A: Physicochemical and Engineering Aspects 156 (1):33-48. https://doi.org/10.1016/S0927-7757(99)00011-4.

Dreyer, A., T. Kirchgeorg, I. Weinberg, and V. Matthias. 2015. "Particle-size distribution of airborne poly- and perfluorinated alkyl substances." Chemosphere 129:142-149. https://doi.org/10.1016/j.chemosphere.2014.06.069.

Dreyer, A., V. Matthias, I. Weinberg, and R. Ebinghaus. 2010. "Wet deposition of poly- and perfluorinated compounds in Northern Germany." Environmental Pollution 158 (5):1221-1227. https://doi.org/10.1016/j.envpol.2010.01.030.

Dreyer, Annekatrin, Ingo Weinberg, Christian Temme, and Ralf Ebinghaus. 2009. "Polyfluorinated Compounds in the Atmosphere of the Atlantic and Southern Oceans: Evidence for a Global Distribution." Environmental Science & Technology 43 (17):6507-6514. https://doi.org/10.1021/es9010465.

Droge, Steven T. J. 2019. "Membrane–Water Partition Coefficients to Aid Risk Assessment of Perfluoroalkyl Anions and Alkyl Sulfates." Environmental Science & Technology 53 (2):760-770. https://doi.org/10.1021/acs.est.8b05052.

Drottar, K.R., and H.O. Krueger. 2000. PFOS: A 96-hr static acute toxicity test with the freshwater mussel (Unio complanatus). Project No. 454A-105, EPA Docket AR226-0091: Wildlife International Ltd.

Drottar, K.R., and H.O. Krueger. 2000. PFOS: A 96-hr toxicity test with the freshwater alga (Selenastrum capricornutum). Project Number 454A-103A. EPA Docket AR226-0085: Ltd. Wildlife International.

Drottar, K.R., and H.O. Krueger. 2000. PFOS: a 96-hr static acute toxicity test with the fathead minnow (Pimephales promelas). Project No. 454-102, EPA Docket AR226-0083: Wildlife International Ltd.

Drottar, K.R., and H.O. Krueger. 2000. PFOS: A 96-hr static acute toxicity test with the saltwater mysid (Mysidopsis bahia) Project No. 454A-101; EPA Docket AR226-0095: Wildlife International Ltd.

Drottar, K.R., and H.O. Krueger. 2000. PFOS: A 96-hr shell deposition test with the eastern oyster (Crassostrea virginica). Project No. 454A-106; EPA Docket AR226-0089: Wildlife International Ltd.

Drottar, K.R., and H.O. Krueger. 2001. PFBS: A semi-static life-cycle toxicity test with the cladoceran (Daphnia magna).

Project Number 454A-130: Wildlife International Ltd.

Drottar, K.R., R.L. Van Hoven, and H.O. Kruger. 2002. Perfluorooctane sulfonate, potassium salt (PFOS): a flow-through bioconcentration test with the bluegill (Lepomis macrochirus) – amended. Project number 454A-134 USEPA Docket AR226-1108: Wildlife International Ltd.

Du, Ziwen, Shubo Deng, Yue Bei, Qian Huang, Bin Wang, Jun Huang, and Gang Yu. 2014. “Adsorption behavior and mechanism of perfluorinated compounds on various adsorbents—A review.” Journal of Hazardous Materials 274:443-454. https://doi.org/10.1016/j.jhazmat.2014.04.038.

Duchesne, Alexandra L., Joshua K. Brown, David J. Patch, David Major, Kela P. Weber, and Jason I. Gerhard. 2020. “Remediation of PFAS-Contaminated Soil and Granular Activated Carbon by Smoldering Combustion.” Environmental Science & Technology 54 (19):12631-12640. https://doi.org/10.1021/acs.est.0c03058.

Dudley, L.A., E.C. Arevalo, and D.R. Knappe. 2015. Removal of Perfluoroalkyl Substances by PAC Adsorption and Anion Exchange. Project #4344: Water Research Foundation.

Dunagan, S., J.G. Brody, R. Morello-Frosch, P. Brown, S. Goho, J. Tovar, S. Patton, and R. Danford. 2013. When Pollution is Personal: Handbook for Reporting Results to Participants in Biomonitoring and Personal Exposure Studies. Silent Spring Institute. https://silentspring.org/sites/default/files/publication/2019-02/personal_exposure_report_handbook.pdf.

DuPont. 2008. Cross-species comparison FRD-902 plasma pharmacokinetics in the rat and primate following intravenous dosing. https://edocs.deq.nc.gov/WaterResources/Browse.aspx?startid=624254&row=1&dbid=0

DuPont. 2009. H-28548: Inhalation Acute Exposure with Anatomic Pathology Evaluation in Rats. Test guideline not identified. . Study No. 17751-723. Newark, DE: E.I. du Pont de Nemours and Company.

DuPont. 2010. GenX Filings with USEPA TSCA section 8(e). https://assets.documentcloud.org/documents/2746960/GenX8eFilings.pdf.

DuPont. 2011. H-28548: Absorption, Distribution, Metabolism, and Elimination in the Mouse. https://edocs.deq.nc.gov/WaterResources/Browse.aspx?startid=624254&row=1&dbid=0

DuPont. 2011. H-28548: Absorption, Distribution, Metabolism, and Elimination in the Rat. https://edocs.deq.nc.gov/WaterResources/Browse.aspx?startid=624254&row=1&dbid=0

EA Engineering. 2021. Report on PFAS destruction testing results at Clean Harbors’ Aragonite, Utah Hazardous Waste Incinerator. https://www.cleanharbors.com/sites/g/files/bdczcs356/files/2022-11/Aragonite%20PFAS%20Destruction%20Test%202021.pdf.

Earthjustice. 2020. PFAS Incineration Suit. https://earthjustice.org/sites/default/files/files/filed_complaint_-_pfas_incineration_suit.pdf

East, Andrew, Richard H. Anderson, and Christopher J. Salice. 2021. “Per- and Polyfluoroalkyl Substances (PFAS) in Surface Water Near US Air Force Bases: Prioritizing Individual Chemicals and Mixtures for Toxicity Testing and Risk Assessment.” Environmental Toxicology and Chemistry 40 (3):859-870. https://doi.org/10.1002/etc.4893.

Eberle, Dylan, Raymond Ball, and Thomas B. Boving. 2017. “Impact of ISCO Treatment on PFAA Co-Contaminants at a Former Fire Training Area.” Environmental Science & Technology 51 (9):5127-5136. https://doi.org/10.1021/acs.est.6b06591.

Ebersbach, Ina, Svenja M. Ludwig, Marc Constapel, and Hans-Willi Kling. 2016. “An alternative treatment method for fluorosurfactant-containing wastewater by aerosol-mediated separation.” Water Research 101:333-340. https://doi.org/10.1016/j.watres.2016.05.063.

Ebrahimi, Farshad, Asa J. Lewis, Christopher M. Sales, Rominder Suri, and Erica R. McKenzie. 2021. “Linking PFAS partitioning behavior in sewage solids to the solid characteristics, solution chemistry, and treatment processes.” Chemosphere 271:129530. https://doi.org/10.1016/j.chemosphere.2020.129530.

ECCC. 2017. Aqueous film-forming foam and the Prohibition of Certain Toxic Substances Regulations. https://www.canada.ca/en/environment-climate-change/services/management-toxic-substances/list-canadian-environmental-protection-act/perfluorooctane-sulfonate/film-forming-foam-prohibition-toxic-substances.html.

ECCC. 2018. "Federal Environmental Quality Guidelines: Perfluorooctane Sulfonate (PFOS)." Last Modified June 2018. accessed 2020. https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/federal-environmental-quality-guidelines-perfluorooctane-sulfonate.html.

ECCC. 2022. "Chapter 2, Forward Regulatory Plan 2022 to 2024, Proposed Prohibition of Certain Toxic Substances Regulations." https://www.canada.ca/en/environment-climate-change/corporate/transparency/acts-regulations/forward-regulatory-plan/2022-2024/chemicals-management.html.

ECHA. 2012. CLH report for 8:2 FTOH. CLH Report. Proposal for Harmonised Classification and Labelling Based on Regulation (EC). March 20, 2012. No. 1272/2008 (CLP Regulation), Annex VI, Part 2: European Chemicals Agency.

ECHA. 2018. Submitted restrictions under consideration. European Chemicals Agency. https://echa.europa.eu/restrictions-under-consideration https://echa.europa.eu/substances-of-very-high-concern-identification/-/substance-rev/20306/term?_viewsubstances_WAR_echarevsubstanceportlet_SEARCH_CRITERIA_EC_NUMBER=206-196-6&_viewsubstances_WAR_echarevsubstanceportlet_DISS=true.

ECHA. 2018. 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctanesulphonic acid. https://echa.europa.eu/fr/registration-dossier/-/registered-dossier/24637/6/2/1.

ECHA. 2021. Opinion on an Annex XV dossier proposing restrictions on undecafluorohexanoic acid (PFHxA), its salts and related substances. Helsinki, Finland. https://echa.europa.eu/documents/10162/97eb5263-90be-ede5-0dd9-7d8c50865c7e.

ECHA. 2023. PFAS Restriction Proposal. European Chemicals Agency. https://echa.europa.eu/sv/-/echa-publishes-pfas-restriction-proposal.

ECOS. 2023. PFAS in Biosolids: A Review of State Efforts & Opportunities for Action. Washington, D.C.: ECOS. https://www.ecos.org/wp-content/uploads/2023/01/PFAS-in-Biosolids-A-Review-of-State-Efforts-and-Opportunities-for-Action.pdf.

ECOS. 2023. Processes and Considerations for Setting State PFAS Standards. Washington, DC: ECOS. https://www.ecos.org/wp-content/uploads/2023/03/2023-ECOS-PFAS-Standards-Paper-Update.pdf.

ECOS-DOD. 2007. Identification and Selection of Toxicity Values/Criteria for Comprehensive Environmental Response, Compensation, and Recovery Act (CERCLA) and Hazardous Waste Site Risk Assessments in the Absence of IRIS Values.

EFSA. 2018. "Risk to human health related to the presence of perfluorooctane sulfonic acid and perfluorooctanoic acid in food." European Food Safety Authority (EFSA) Journal 16 (12):5194. 10.2903/j.efsa.2018.5194.

EFSA. 2020. "PFAS in Food: EFSA assess risks and sets tolerable intake." European Food Safety Authority. accessed 2022. https://www.efsa.europa.eu/en/news/pfas-food-efsa-assesses-risks-and-sets-tolerable-intake.

Ege, S. N. 1999. Organic Chemistry: Structure and Reactivity: Fourth Edition. Boston, MA: Houghton Mifflin Company. ISBN No. 0395902231.

Eggen, Trine, Monika Moeder, and Augustine Arukwe. 2010. "Municipal landfill leachates: A significant source for new and emerging pollutants." Science of The Total Environment 408 (21):5147-5157. https://doi.org/10.1016/j.scitotenv.2010.07.049.

EGLE, MI. 2021. Statewide Wastewater Treatment Plant and Biosolids PFAS Study. FIeld Reports Summary. https://www.michigan.gov/egle/about/organization/Water-Resources/biosolids/pfas-related.

Ellis, David A., Jonathan W. Martin, Amila O. De Silva, Scott A. Mabury, Michael D. Hurley, Mads P. Sulbaek Andersen, and Timothy J. Wallington. 2004. “Degradation of Fluorotelomer Alcohols: A Likely Atmospheric Source of Perfluorinated Carboxylic Acids.” Environmental Science & Technology 38 (12):3316-3321. 10.1021/es049860w.

Emmett, Edward A., and Chintan Desai. 2010. “Community First Communication: Reversing Information Disparities to Achieve Environmental Justice.” Environmental Justice 3 (3):79-84. 10.1089/env.2009.0037.

Emmett, E. A., F. S. Shofer, H. Zhang, D. Freeman, C. Desai, and L. M. Shaw. 2006. “Community exposure to perfluorooctanoate: relationships between serum concentrations and exposure sources.” J Occup Environ Med 48 (8):759-70. 10.1097/01.jom.0000232486.07658.74.

Emmett, Edward Anthony, Hong Zhang, Frances Susan Shofer, Nancy Rodway, Chintan Desai, David Freeman, and Mary Hufford. 2009. “Development and Successful Application of a “Community-First” Communication Model for Community-based Environmental Health Research.” Journal of Occupational and Environmental Medicine 51 (2).

Endpoint Consulting. 2016. Bench-Scale VEG Research and Development Study: Implementation Memorandum for Ex-Situ Thermal Desorption of Perfluoroalkyl Compounds (PFCs) in Soils. http://www.endpoint-inc.com/wp-content/uploads/2016/05/VEG-Bench-Scale-PFCs-Soil.pdf

Engström, K., A. Axmon, C. Nielsen, and A. Rignell-Hydbom. 2022. “High in Utero Exposure to Perfluoroalkyl Substances from Drinking Water and Birth Weight: A Cohort Study among Infants in Ronneby, Sweden.” Int J Environ Res Public Health 19 (4). 10.3390/ijerph19042385.

Ensch, Mary, Cory A. Rusinek, Michael F. Becker, and Thomas Schuelke. 2020. “A combined current density technique for the electrochemical oxidation of perfluorooctanoic acid (PFOA) with boron-doped diamond.” Water and Environment Journal n/a (n/a). https://doi.org/10.1111/wej.12616.

Environment Canada. 2006. Ecological Screening Assessment Report on Perfluorooctane Sulfonate, Its Salts, and Its Precursors that Contain the C8F17SO2 or C8F17SO3 or C8F17SO2N Moiety. https://www.ec.gc.ca/lcpe-cepa/documents/substances/spfo-pfos/ecological_sar_pfos_eng.pdf

Environment Canada. 2012. Screening Assessment Report on Perfluorooctanoic Acid, Its Salts, and Its Precursors. https://www.ec.gc.ca/ese-ees/370AB133-3972-454F-A03A-F18890B58277/PFOA_EN.pdf

Environmental Protection Authority Victoria. 2019. PFAS in Victorian waterfowl. Publication 1734. https://ref.epa.vic.gov.au/~/media/Publications/1734.pdf.

Environmental Working Group and Northeastern University Social Science Environmental Health Research Institute. 2017. Mapping A Contamination Crisis. http://www.ewg.org/research/mapping-contamination-crisis#.WbbRI-SWzcs.

Enviropacific. 2017. Treatment of PFAS in Soils, Sediments and Water. http://www.enviropacific.com.au/wp-content/uploads/2016/09/Enviropacific_Treatment-of-PFAS.pdf

EPA Science Advisory Board. 2006. Science Advisory Board Review of EPA’s Draft Risk Assessment of Potential Human Health Effects Associated with PFOA and Its Salts, May 30, 2006. EPA-SAB-06-006.

Erhunse, A. 2010. An assessment of perfluoroalkyl substances bioavailability and policy implications for water quality and biota in the Lower Apalachicola River and Estuary. Florida A&M University: Environmental Sciences Institute.

Ericson Jogsten, I., M. Nadal, B. van Bavel, G. Lindström, and J. L. Domingo. 2012. “Per- and polyfluorinated compounds (PFCs) in house dust and indoor air in Catalonia, Spain: Implications for human exposure.” Environment International 39 (1):172-180. https://doi.org/10.1016/j.envint.2011.09.004.

Ericson Jogsten, Ingrid, and L. W. Yeung. 2017. Analysis of ultra-short chain perfluoroalkyl substances in Swedish environmental waters. Orebro, Sweden: Orebro University. http://www.diva-portal.org/smash/get/diva2:1178319/FULLTEXT01.pdf.

Eriksson, Ulrika, Peter Haglund, and A. Karrman. 2016. Screening of PFASs in sludge and water from waste water treatment plants. Umea, Sweden: Umea University.

Eriksson, Ulrika, Peter Haglund, and Anna Karrman. 2017. “Contribution of precursor compounds to the release of per-and polyfluoroalkyl substances (PFASs) from waste water treatment plants (WWTPs).” Journal of Environmental Sciences 61:80-90. https://doi.org/10.1016/j.jes.2017.05.004.

Eriksson, Ulrika, Anna Karrman, Anna Rotander, Bjørg Mikkelsen, and Maria Dam. 2013. “Perfluoroalkyl substances (PFASs) in food and water from Faroe Islands.” Environmental Science and Pollution Research 20:7940-7948. https://doi.org/10.1007/s11356-013-1700-3.

Eriksson, Ulrika, Jochen F. Mueller, Leisa-Maree L. Toms, Peter Hobson, and Anna Kärrman. 2017. “Temporal trends of PFSAs, PFCAs and selected precursors in Australian serum from 2002 to 2013.” Environmental Pollution 220:168-177. https://doi.org/10.1016/j.envpol.2016.09.036.

Eschauzier, Christian, Erwin Beerendonk, Petra Scholte-Veenendaal, and Pim De Voogt. 2012. “Impact of Treatment Processes on the Removal of Perfluoroalkyl Acids from the Drinking Water Production Chain.” Environmental Science & Technology 46 (3):1708-1715. 10.1021/es201662b.

Escher, Beate I., Ruben Abagyan, Michelle Embry, Nils Klüver, Aaron D. Redman, Christiane Zarfl, and Thomas F. Parkerton. 2020. “Recommendations for Improving Methods and Models for Aquatic Hazard Assessment of Ionizable Organic Chemicals.” Environmental Toxicology and Chemistry 39 (2):269-286. https://doi.org/10.1002/etc.4602.

ESTCP. 2011. Final Report, Assessing Alternative Endpoints for Groundwater Remediation at Contaminated Sites. ESTCP Project ER-200832.

ESTCP. 2022. Final Report: Ex Situ Soil Washing to Remove PFAS Adsorbed to Soils from Source Zones. ESTCP Project ER20-5258.

Eurofins. 2019. Analysis Report, Franklin MA.

European Commission. 2017. Commission regulation (EU) 2017/1000, amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards perfluorooctanoic acid (PFOA), its salts and PFOA-related substances. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R1000&from=EN.

European Commission. 2020. The Use of PFAS and Fluorine-Free Alternatives in Fire-Fighting Foams. Brussels: DG Environment / European Chemicals Agency (ECHA). https://echa.europa.eu/documents/10162/28801697/pfas_flourine-free_alternatives_fire_fighting_en.pdf/d5b24e2a-d027-0168-cdd8-f723c675fa98.

European Commission. 2020. Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions: Chemical Strategy for sustainability. 52020DC0667. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:667:FIN.

European Commission. 2021. Commission Regulation (EU) 2021/1297 amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council as regards perfluorocarboxylic acids containing 9 to 14 carbon atoms in the chain (C9-C14 PFCAs), their salts and C9-C14. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1297&rid=3.

European Food Safety Authority. 2018. “The 2016 European Union report on pesticide residues in food.” EFSA Journal 16 (7):e05348. https://doi.org/10.2903/j.efsa.2018.5348.

European Union. 2011. PFOS EQS Dossier 2011. EQSD 2008/105/EC: Sub-Group on Review of the Priority Substances List.

European Union. 2013. Directive 2013/39/EU amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy. Official Journal of the European Union.

European Union. 2019. “Regulation on Persistent Organic Pollutants. Annex I, Part A.” https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02019R1021-20210315#tocId2.

Evich, Marina G., Mary J. B. Davis, James P. McCord, Brad Acrey, Jill A. Awkerman, Detlef R. U. Knappe, Andrew B. Lindstrom, Thomas F. Speth, Caroline Tebes-Stevens, Mark J. Strynar, Zhanyun Wang, Eric J. Weber, W. Matthew

Henderson, and John W. Washington. “Per- and polyfluoroalkyl substances in the environment.” Science 375 (6580):eabg9065. 10.1126/science.abg9065.

Executive Order 12898. 1994. Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations. 59 Federal Register 7629.

FAA. 2006. Aqueous Film Forming Foam (AFFF) meeting MIL-F-24385. FAA CertAlert No. 06-02.

FAA. 2016. Update on Mil-Spec Aqueous Film Forming Foam (AFFF). FAA CertAlert No. 16-05. https://www.faa.gov/airports/airport_safety/certalerts/media/part-139-cert-alert-16-05-Mil-Spec-AFFF-website-update.pdf.

FAA. 2018. FAA Reauthorization Act of 2018. P.L. 115-254. https://www.congress.gov/bill/115th-congress/house-bill/302/text?q=%7B%22search%22%3A%5B%22FAA+Reauthorization%22%5D%7D&r=2.

FAA. 2020. “FAA Opens One-of-a-Kind Fire Research Facility in Atlanta City.” Last Modified January 14, 2020. accessed 2020. https://www.faa.gov/news/updates/?newsId=94946.

FAA. 2021. National Part 139 Cert Alert. Extinguishing Agent Requirements. https://www.faa.gov/airports/airport_safety/certalerts/media/part-139-cert-alert-21-05-Extinguishing-Agent-Requirements.pdf.

FAA. 2023. CertAlerts for Part 139 Airport Certification. Washington, D.C. https://www.faa.gov/airports/airport_safety/certalerts.

FAA. 2023. Part 139 CerAlert 23-01: New Military Specification for Performance-Based Standards for Fluorine-Free Aircraft Fire Fighting Foam. https://www.faa.gov/airports/airport_safety/certalerts/part_139_certalert_23_01.

Fabbri, Rita, Michele Montagna, Teresa Balbi, Enrico Raffo, Franca Palumbo, and Laura Canesi. 2014. “Adaptation of the bivalve embryotoxicity assay for the high throughput screening of emerging contaminants in Mytilus galloprovincialis.” Marine Environmental Research 99:1-8. https://doi.org/10.1016/j.marenvres.2014.05.007.

Fair, P. A., T. Romano, A. M. Schaefer, J. S. Reif, G. D. Bossart, M. Houde, D. C. Muir, J. Adams, C. Rice, T. C. Hulsey, and M. Peden-Adams. 2013. “Associations between perfluoroalkyl compounds and immune and clinical chemistry parameters in highly exposed bottlenose dolphins (Tursiops truncatus).” Environmental Toxicology and Chemistry 32 (4):736-746. https://doi.org/10.1002/etc.2122.

Fakouri Baygi, Sadjad, Bernard S. Crimmins, Philip K. Hopke, and Thomas M. Holsen. 2016. “Comprehensive Emerging Chemical Discovery: Novel Polyfluorinated Compounds in Lake Michigan Trout.” Environmental Science & Technology 50 (17):9460-9468. https://doi.org/10.1021/acs.est.6b01349.

Falk, Sandy, Klaus Failing, Sebastian Georgii, Hubertus Brunn, and Thorsten Stahl. 2015. “Tissue specific uptake and elimination of perfluoroalkyl acids (PFAAs) in adult rainbow trout (Oncorhynchus mykiss) after dietary exposure.” Chemosphere 129:150-156. https://doi.org/10.1016/j.chemosphere.2014.06.061.

Fang, Shuhong, Xinwei Chen, Shuyan Zhao, Yifeng Zhang, Weiwei Jiang, Liping Yang, and Lingyan Zhu. 2014. “Trophic Magnification and Isomer Fractionation of Perfluoroalkyl Substances in the Food Web of Taihu Lake, China.” Environmental Science & Technology 48 (4):2173-2182. https://doi.org/10.1021/es405018b.

Fang, Xuemei, Yixing Feng, Zhimin Shi, and Jiayin Dai. 2009. “Alterations of Cytokines and MAPK Signaling Pathways are Related to the Immunotoxic Effect of Perfluorononanoic Acid.” Toxicological Sciences 108 (2):367-376. https://doi.org/10.1093/toxsci/kfp019.

Fang, Xuemei, Yixing Feng, Jianshe Wang, and Jiayin Dai. 2010. “Perfluorononanoic acid-induced apoptosis in rat spleen involves oxidative stress and the activation of caspase-independent death pathway.” Toxicology 267 (1):54-59. https://doi.org/10.1016/j.tox.2009.10.020.

Fang, Xuemei, Lianjun Zhang, Yixing Feng, Yong Zhao, and Jiayin Dai. 2008. “Immunotoxic Effects of Perfluorononanoic Acid on BALB/c Mice.” Toxicological Sciences 105 (2):312-321. https://doi.org/10.1093/toxsci/kfn127.

Farhat, S.K., C.J. Newell, R.W. Falta, and K. Lynch. 2018. User's Manual. A Pratical Approach for Modeling Matrix Diffusion Effects in REMChlor. ESTCP Project ER-201426. https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Persistent-Contamination/ER-201426#factsheet-19113-publications.

Farhat, Shahla K., Charles J. Newell, Sophia A. Lee, Brian B. Looney, and Ronald W. Falta. 2022. "Impact of matrix diffusion on the migration of groundwater plumes for Perfluoroalkyl acids (PFAAs) and other non-degradable compounds." Journal of Contaminant Hydrology 247:103987. https://doi.org/10.1016/j.jconhyd.2022.103987.

Fasano, William J., Stephen C. Carpenter, Shawn A. Gannon, Timothy A. Snow, Judith C. Stadler, Gerald L. Kennedy, Robert C. Buck, Stephen H. Korzeniowski, Paul M. Hinderliter, and Raymond A. Kemper. 2006. "Absorption, Distribution, Metabolism, and Elimination of 8-2 Fluorotelomer Alcohol in the Rat." Toxicological Sciences 91 (2):341-355. 10.1093/toxsci/kfj160.

Fasano, W. J., G. L. Kennedy, B. Szostek, D. G. Farrar, R. J. Ward, L. Haroun, and P. M. Hinderliter. 2005. "Penetration of ammonium perfluorooctanoate through rat and human skin in vitro." Drug Chem Toxicol 28 (1):79-90. https://doi.org/10.1081/dct-39707.

Fasano, William J., Lisa M. Sweeney, Michael P. Mawn, Diane L. Nabb, Bogdan Szostek, Robert C. Buck, and Michael L. Gargas. 2009. "Kinetics of 8-2 fluorotelomer alcohol and its metabolites, and liver glutathione status following daily oral dosing for 45 days in male and female rats." Chemico-Biological Interactions 180 (2):281-295. https://doi.org/10.1016/j.cbi.2009.03.015.

Fauvelle, Vincent, Natalia Montero, Jochen F. Mueller, Andrew Banks, Nicolas Mazzella, and Sarit L. Kaserzon. 2017. "Glyphosate and AMPA passive sampling in freshwater using a microporous polyethylene diffusion sampler." Chemosphere 188:241-248. https://doi.org/10.1016/j.chemosphere.2017.08.013.

Favara, Paul, John Tunks, Jim Hatton, and William DiGuiseppi. 2016. "Sustainable Remediation Considerations for Treatment of 1,4-Dioxane in Groundwater." Remediation Journal 27 (1):133-158. https://doi.org/10.1002/rem.21501.

Favreau, Philippe, Chantal Poncioni-Rothlisberger, Benjamin J. Place, Harold Bouchex-Bellomie, Andreas Weber, Josef Tremp, Jennifer A. Field, and Marcel Kohler. 2017. "Multianalyte profiling of per- and polyfluoroalkyl substances (PFASs) in liquid commercial products." Chemosphere 171:491-501. https://doi.org/10.1016/j.chemosphere.2016.11.127.

FDA. 2018. Inventory of Effective Food Contact Substance Notifications. https://www.accessdata.fda.gov/scripts/fdcc/?set=FCN.

FDA. 2023. "Inventory of Effective Food Contact Substance (FCS) Notifications." Last Modified May 31, 2023. accessed 2023. https://www.cfsanappsexternal.fda.gov/scripts/fdcc/index.cfm?set=FCN&sort=FCN_No&order=DESC&startrow=601&type=basic&search=.

FDSA. 2021. News Release, F3 Classification List, Replacements for AFFF containing PFAS. Foam Exposure Committee Fire Dept Service Announcement. https://www.fdsoa.org/resources/Foam%20Exposure%20Bulletins/news%20release%20F3%20Classification%20List%2003%2015%202021.pdf.

FDSOA. 2021. "Foam Expsoure Information." Fire Department Safety Officers Association. accessed 2021. https://www.fdsoa.org/Foam-Exposure-Info.

Felizeter, Sebastian, Heinrich Jürling, Matthias Kotthoff, Pim De Voogt, and Michael S. McLachlan. 2021. "Uptake of perfluorinated alkyl acids by crops: results from a field study." Environmental Science: Processes & Impacts 23 (8):1158-1170. 10.1039/D1EM00166C.

FEMA. 2019. Guidance for Stakeholder Engagement. Introduction and key terms. Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/2020-02/Stakeholder_Engagement_Introduction_Guidance_Nov_2019.pdf.

Feng, X., X. Cao, S. Zhao, X. Wang, X. Hua, L. Chen, and L. Chen. 2017. "Exposure of Pregnant Mice to

Perfluorobutanesulfonate Causes Hypothyroxinemia and Developmental Abnormalities in Female Offspring." Toxicol Sci 155 (2):409-419. 10.1093/toxsci/kfw219.

Feng, Y., X. Fang, Z. Shi, M. Xu, and J. Dai. 2010. "Effects of PFNA exposure on expression of junction-associated molecules and secretory function in rat Sertoli cells." Reprod Toxicol 30 (3):429-37. 10.1016/j.reprotox.2010.05.010.

Feng, Yixing, Zhimin Shi, Xuemei Fang, Muqi Xu, and Jiayin Dai. 2009. "Perfluorononanoic acid induces apoptosis involving the Fas death receptor signaling pathway in rat testis." Toxicology Letters 190 (2):224-230. https://doi.org/10.1016/j.toxlet.2009.07.020.

Fenton, Suzanne E., Alan Ducatman, Alan Boobis, Jamie C. DeWitt, Christopher Lau, Carla Ng, James S. Smith, and Stephen M. Roberts. 2020. "Per- and Polyfluoroalkyl Substance Toxicity and Human Health Review: Current State of Knowledge and Strategies for Informing Future Research." Environmental Toxicology and Chemistry n/a (n/a). https://doi.org/10.1002/etc.4890.

Fernandez, S. R., C. Kwiatkowski, and T. Bruton. 2021. Building a Better World. Eliminating Unnecessary PFAS in Building Materials. Green Science Policy Institute. https://greensciencepolicy.org/docs/pfas-building-materials-2021.pdf.

Fernández-Sanjuan, María, Melissa Faria, Silvia Lacorte, and Carlos Barata. 2013. "Bioaccumulation and effects of perfluorinated compounds (PFCs) in zebra mussels (Dreissena polymorpha)." Environmental Science and Pollution Research 20 (4):2661-2669. 10.1007/s11356-012-1158-8.

Fey, M. E., P. E. Goodrum, N. R. Razavi, C. M. Whipps, S. Fernando, and J. K. Anderson. 2022. "Is Mixtures' Additivity Supported by Empirical Data? A Case Study of Developmental Toxicity of PFOS and 6:2 FTS in Wildtype Zebrafish Embryos." Toxics 10 (8). 10.3390/toxics10080418.

FFFC. 2016. Best Practice Guidance for Use of Class B Firefighting Foams. Arlington, VA: Fire Fighting Foam Coalition. https://www.fffc.org.

FFFC. 2018. Best Practice Guidance for Fluorinated Firefighting Foams Q&A. Arlington, VA: Fire Fighting Foam Coalition. https://www.americanchemistry.com/industry-groups/alliance-for-telomer-chemistry-stewardship-atcs/resources/best-practice-guidance-for-fluorinated-firefighting-foams.

Field, J., D. Sedlak, and L. Alvarez-Cohen. 2017. Final Report – Characterization of the Fate and Biotransformation of Fluorochemicals in AFFF-Contaminated Groundwater at Fire/Crash Testing Military Sites. SERDP Project ER-2128.

Field, Jennifer A., and Jimmy Seow. 2017. "Properties, occurrence, and fate of fluorotelomer sulfonates." Critical Reviews in Environmental Science and Technology 47 (8):643-691. 10.1080/10643389.2017.1326276.

Field Jennifer, A., Trever Schwichtenberg, R.A. Deeb, Elisabeth L. Hawley, Claire Sayler, Dorin Bogdan, E. Schaefer Charles, B. DiGuiseppi, and A. Struse. 2021. Assessing the Potential for Bias in PFAS Concentrations during Groundwater and Surface Water Sampling. SERDP Project ER19-1205. https://www.serdp-estcp.org.

Filipovic, Marko, and Urs Berger. 2015. "Are perfluoroalkyl acids in waste water treatment plant effluents the result of primary emissions from the technosphere or of environmental recirculation?" Chemosphere 129:74-80. https://doi.org/10.1016/j.chemosphere.2014.07.082.

Filipovic, Marko, Hjalmar Laudon, Michael S. McLachlan, and Urs Berger. 2015. "Mass Balance of Perfluorinated Alkyl Acids in a Pristine Boreal Catchment." Environmental Science & Technology 49 (20):12127-12135. 10.1021/acs.est.5b03403.

Fitzgerald, N.J., A. Wargenau, C. Sorenson, J. Pedersen, N. Tufenkji, P.J. Novak, and M.F. Simcik. 2018. "Partitioning and accumulation of perfluoroalkyl substances in model lipid bilayers and bacteria." Environmental Science & Technology 52 (18):10433-40.

FL DEP. 2020. Per and Polyfluoroalkyl Substances (PFAS) Dynamic Plan. Florida Department of Environmental Protection Division of Waste Management. https://floridadep.gov/sites/default/files/Dynamic_Plan_Revised_Feb2021.pdf.

Fliedner, A., H. Rüdel, N. Lohmann, G. Buchmeier, and J. Koschorreck. 2018. "Biota monitoring under the Water Framework Directive: On tissue choice and fish species selection." Environmental Pollution 235:129-140.

Flores, C., F. Ventura, J. Martin-Alonso, and J. Caixach. 2013. “Occurrence of perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) in N.E. Spanish surface waters and their removal in a drinking water treatment plant that combines conventional and advanced treatments in parallel lines.” Science of the Total Environment 461-462:618-626. https://doi.org/10.1016/j.scitotenv.2013.05.026.

FluoroCouncil. 2017. “Research Relevant to Short-Chain PFAS.”

FluoroCouncil. 2018. “Applications.”

Flynn, R. Wesley, Michael F. Chislock, Megan E. Gannon, Stephanie J. Bauer, Brian J. Tornabene, Jason T. Hoverman, and Maria S. Sepúlveda. 2019. “Acute and chronic effects of perfluoroalkyl substance mixtures on larval American bullfrogs (Rana catesbeiana).” Chemosphere 236:124350. https://doi.org/10.1016/j.chemosphere.2019.124350.

Flynn, R. Wesley, Gary Hoover, Michael Iacchetta, Samuel Guffey, Chloe de Perre, Belinda Huerta, Weiming Li, Jason T. Hoverman, Linda Lee, and Maria S. Sepúlveda. 2022. “Comparative Toxicity of Aquatic Per- and Polyfluoroalkyl Substance Exposure in Three Species of Amphibians.” Environmental Toxicology and Chemistry 41 (6):1407-1415. https://doi.org/10.1002/etc.5319.

Flynn, R. Wesley, Michael Iacchetta, Chloe de Perre, Linda Lee, Maria S. Sepúlveda, and Jason T. Hoverman. 2021. “Chronic Per-/Polyfluoroalkyl Substance Exposure Under Environmentally Relevant Conditions Delays Development in Northern Leopard Frog (Rana pipiens) Larvae.” Environmental Toxicology and Chemistry 40:711-716. https://doi.org/10.1002/etc.4690.

Forrester, E., and J. Matthis. 2018. Treatment Solutions for PFAS Removal: Evaluating Total Cost.

Fort, Douglas J., Michael B. Mathis, Patrick D. Guiney, and John A. Weeks. 2019. “Evaluation of the developmental toxicity of perfluorooctanesulfonate in the Anuran, Silurana tropicalis.” Journal of Applied Toxicology 39 (2):365-374. https://doi.org/10.1002/jat.3727.

Franklin, James. 2016. “How reliable are field-derived biomagnification factors and trophic magnification factors as indicators of bioaccumulation potential? Conclusions from a case study on per- and polyfluoroalkyl substances.” Integrated Environmental Assessment and Management 12 (1):6-20. http://dx.doi.org/10.1002/ieam.1642.

Franko, J., B. J. Meade, H. F. Frasch, A. M. Barbero, and S. E. Anderson. 2012. “Dermal penetration potential of perfluorooctanoic acid (PFOA) in human and mouse skin.” J Toxicol Environ Health A 75 (1):50-62. 10.1080/15287394.2011.615108.

Fraser, Alicia J., Thomas F. Webster, Deborah J. Watkins, Jessica W. Nelson, Heather M. Stapleton, Antonia M. Calafat, Kayoko Kato, Mahiba Shoeib, Verónica M. Vieira, and Michael D. McClean. 2012. “Polyfluorinated Compounds in Serum Linked to Indoor Air in Office Environments.” Environmental Science & Technology 46 (2):1209-1215. 10.1021/es2038257.

Frawley, Rachel P., Matthew Smith, Mark F. Cesta, Schantel Hayes-Bouknight, Chad Blystone, Grace E. Kissling, Shawn Harris, and Dori Germolec. 2018. “Immunotoxic and hepatotoxic effects of perfluoro-n-decanoic acid (PFDA) on female Harlan Sprague–Dawley rats and B6C3F1/N mice when administered by oral gavage for 28 days.” Journal of Immunotoxicology 15 (1):41-52. 10.1080/1547691X.2018.1445145.

Freberg, Baard Ingegerdsson, Line Småstuen Haug, Raymond Olsen, Hanne Line Daae, Merete Hersson, Cathrine Thomsen, Syvert Thorud, Georg Becher, Paal Molander, and Dag G. Ellingsen. 2010. “Occupational Exposure to Airborne Perfluorinated Compounds during Professional Ski Waxing.” Environmental Science & Technology 44 (19):7723-7728. 10.1021/es102033k.

Fredriksson, F. 2016. Analysis of Per- and Polyfluoroalkyl Substances (PFASs) in African Darter (Anhinga rufa) Eggs along Vaal River, South Africa. Örebro University School of Science and Technology.

Fredriksson, Felicia, Ulrika Eriksson, Anna Kärrman, and Leo W. Y. Yeung. 2022. “Per- and polyfluoroalkyl substances (PFAS) in sludge from wastewater treatment plants in Sweden — First findings of novel fluorinated copolymers in Europe including temporal analysis.” Science of The Total Environment 846:157406. https://doi.org/10.1016/j.scitotenv.2022.157406.

Fricke, M., and U. Lahl. 2005. Risk Evaluation of Perfluorinated Surfactants as Contribution to the Current Debate on the EU Commission's REACH Document. UWSF-Z Umweltchem kotox.

Frisbee, S. J., A. P. Brooks, Jr., A. Maher, P. Flensborg, S. Arnold, T. Fletcher, K. Steenland, A. Shankar, S. S. Knox, C. Pollard, J. A. Halverson, V. M. Vieira, C. Jin, K. M. Leyden, and A. M. Ducatman. 2009. "The C8 health project: design, methods, and participants." Environ Health Perspect 117 (12):1873-82. 10.1289/ehp.0800379.

Frisbee, Stephanie J., Anoop Shankar, Sarah S. Knox, Kyle Steenland, David A. Savitz, Tony Fletcher, and Alan M. Ducatman. 2010. "Perfluorooctanoic Acid, Perfluorooctanesulfonate, and Serum Lipids in Children and Adolescents: Results from the C8 Health Project." Archives of Pediatrics & Adolescent Medicine 164 (9):860-869. 10.1001/archpediatrics.2010.163.

Frömel, T., C. Gremmel, I. Dimzon, and P. de Voogt. 2016. Investigations on the presence and behavior of precursors to perfluoroalkyl substances in the environment as a preparation of regulatory measures. https://www.umweltbundesamt.de/publikationen/investigations-on-the-presence-behavior-of.

Fromme, Hermann, Annekatrin Dreyer, Silvio Dietrich, Ludwig Fembacher, Thomas Lahrz, and Wolfgang Völkel. 2015. "Neutral polyfluorinated compounds in indoor air in Germany – The LUPE 4 study." Chemosphere 139:572-578. https://doi.org/10.1016/j.chemosphere.2015.07.024.

Fromme, Hermann, Christine Mosch, Maria Morovitz, Irene Alba-Alejandre, Sigrun Boehmer, Mandy Kiranoglu, Fabienne Faber, Iris Hannibal, Orsolya Genzel-Boroviczény, Berthold Koletzko, and Wolfgang Völkel. 2010. "Pre- and Postnatal Exposure to Perfluorinated Compounds (PFCs)." Environmental Science & Technology 44 (18):7123-7129. https://doi.org/10.1021/es101184f.

Fromme, Hermann, Sheryl A. Tittlemier, Wolfgang Völkel, Michael Wilhelm, and Dorothee Twardella. 2009. "Perfluorinated compounds – Exposure assessment for the general population in western countries." International Journal of Hygiene and Environmental Health 212 (3):239-270. https://doi.org/10.1016/j.ijheh.2008.04.007.

Fromme, Hermann, Mandy Wöckner, Eike Roscher, and Wolfgang Völkel. 2017. "ADONA and perfluoroalkylated substances in plasma samples of German blood donors living in South Germany." International Journal of Hygiene and Environmental Health 220 (2):455-460. https://doi.org/10.1016/j.ijheh.2016.12.014.

FRTR. 2020. "Technology Profile: Soil Washing." Federal Remediation Technologies Roundtable. accessed 2023. https://www.frtr.gov/matrix/Soil-Washing/.

Fuentes, S., P. Vicens, M. T. Colomina, and J. L. Domingo. 2007. "Behavioral effects in adult mice exposed to perfluorooctane sulfonate (PFOS)." Toxicology 242 (1-3):123-9. https://doi.org/10.1016/j.tox.2007.09.012.

Fuerstenau, D. W. 1956. "Streaming Potential Studies on Quartz in Solutions of Aminium Acetates in Relation to the Formation of Hemi- micelles at the Quartz-Solution Interface." The Journal of Physical Chemistry 60 (7):981-985. https://doi.org/10.1021/j150541a039.

Fujii, Yukiko, Kouji H. Harada, and Akio Koizumi. 2013. "Occurrence of perfluorinated carboxylic acids (PFCAs) in personal care products and compounding agents." Chemosphere 93 (3):538-544. https://doi.org/10.1016/j.chemosphere.2013.06.049.

Furl, C., and C. Meredith. 2010. Perfluorinated compounds in Washington rivers and lakes. Publication Number 10-03-034. Olympia, WA. https://fortress.wa.gov/ecy/publications/summarypages/1003034.html.

Furman, Olha, S., Amy Teel, L., Mushtaque Ahmad, Marissa Merker, C., and Richard Watts, J. 2011. "Effect of Basicity on Persulfate Reactivity." Journal of Environmental Engineering 137 (4):241-247. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000323.

Furst, C., C. Weible, and C. Salice. 2019. "Exploring the effects of exposure from common perfluoroalkyl substances (PFASs) on brown anoles (Anolis sagrei)." 40th Annual North American Meeting of the Society of Environmental Toxicology and Chemistry (SETAC), Toronto, Ontario, Canada, November 3-7, 2019.

Furuta, M., M. Yamaguchi, T. Tsukamoto, B. Yim, C. E. Stavarache, K. Hasiba, and Y. Maeda. 2004. "Inactivation of Escherichia coli by ultrasonic irradiation." Ultrasonics Sonochemistry 11 (2):57-60.

https://doi.org/10.1016/S1350-4177(03)00136-6.

Gaines, Linda G. T. 2022. “Historical and current usage of per- and polyfluoroalkyl substances (PFAS): A literature review.” American Journal of Industrial Medicine:1-26. https://doi.org/10.1002/ajim.23362.

Gaines, Linda G. T., Gabriel Sinclair, and Antony J. Williams. 2023. “A proposed approach to defining per- and polyfluoroalkyl substances (PFAS) based on molecular structure and formula.” Integrated Environmental Assessment and Management n/a (n/a). https://doi.org/10.1002/ieam.4735.

Galatius, Anders, Rossana Bossi, Christian Sonne, Frank Farsø Rigét, Carl Kinze, Christina Lockyer, Jonas Teilmann, and Rune Dietz. 2013. “PFAS profiles in three North Sea top predators: Metabolic differences among species?” Environmental Science and Pollution Research 20:8013-8020. https://doi.org/10.1007/s11356-013-1633-x.

Gallen, C., G. Eaglesham, D. Drage, T. Hue Nguyen, and J. F. Mueller. 2018. “A mass estimate of perfluoroalkyl substance (PFAS) release from Australian wastewater treatment plants.” Chemosphere 208:975-983. https://doi.org/10.1016/j.chemosphere.2018.06.024.

Gallo, Valentina, Giovanni Leonardi, Bernd Genser, Maria-Jose Lopez-Espinosa, J. Frisbee Stephanie, Lee Karlsson, M. Ducatman Alan, and Tony Fletcher. 2012. “Serum Perfluorooctanoate (PFOA) and Perfluorooctane Sulfonate (PFOS) Concentrations and Liver Function Biomarkers in a Population with Elevated PFOA Exposure.” Environmental Health Perspectives 120 (5):655-660. 10.1289/ehp.1104436.

Galloway, Jason E., Anjelica V. P. Moreno, Andrew B. Lindstrom, Mark J. Strynar, Seth Newton, Andrew A. May, and Linda K. Weavers. 2020. “Evidence of Air Dispersion: HFPO–DA and PFOA in Ohio and West Virginia Surface Water and Soil near a Fluoropolymer Production Facility.” Environmental Science & Technology 54 (12):7175-7184. https://doi.org/10.1021/acs.est.9b07384.

Gannon, S. A., W. J. Fasano, M. P. Mawn, D. L. Nabb, R. C. Buck, L. W. Buxton, G. W. Jepson, and S. R. Frame. 2016. “Absorption, distribution, metabolism, excretion, and kinetics of 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propanoic acid ammonium salt following a single dose in rat, mouse, and cynomolgus monkey.” Toxicology 340:1-9. https://doi.org/10.1016/j.tox.2015.12.006.

Gao, Yan, Jianjie Fu, Huiming Cao, Yawei Wang, Aiqian Zhang, Yong Liang, Thanh Wang, Chunyan Zhao, and Guibin Jiang. 2015. “Differential Accumulation and Elimination Behavior of Perfluoroalkyl Acid Isomers in Occupational Workers in a Manufactory in China.” Environmental Science & Technology 49 (11):6953-6962. https://doi.org/10.1021/acs.est.5b00778.

García, Raymmah Aleyda, Aurea C. Chiaia-Hernández, Pablo A. Lara-Martin, Martin Loos, Juliane Hollender, Karl Oetjen, Christopher P. Higgins, and Jennifer A. Field. 2019. “Suspect Screening of Hydrocarbon Surfactants in AFFFs and AFFF-Contaminated Groundwater by High-Resolution Mass Spectrometry.” Environmental Science & Technology 53 (14):8068-8077. 10.1021/acs.est.9b01895.

Garnett, Jack, Crispin Halsall, Anna Vader, Hanna Joerss, Ralf Ebinghaus, Amber Leeson, and Peter M. Wynn. 2021. “High Concentrations of Perfluoroalkyl Acids in Arctic Seawater Driven by Early Thawing Sea Ice.” Environmental Science & Technology 55 (16):11049-11059. 10.1021/acs.est.1c01676.

Gassmann, Matthias, Eva Weidemann, and Thorsten Stahl. 2021. “Combined leaching and plant uptake simulations of PFOA and PFOS under field conditions.” Environmental Science and Pollution Research 28 (2):2097-2107. https://doi.org/10.1007/s11356-020-10594-6.

Gauthier, Suzanne A., and Scott A. Mabury. 2005. “Aqueous photolysis of 8:2 fluorotelomer alcohol.” Environmental Toxicology and Chemistry 24 (8):1837-1846. 10.1897/04-591R.1.

Gaylard, S. 2017. Per and polyfluorinated alkyl substances (PFAS) in the marine environment – Preliminary ecological findings. Adelaide, SA: Environment Protection Authority of South Australia. https://www.epa.sa.gov.au/files/12580_report_pfas_marine.pdf.

Ge, H., E. Yamazaki, N. Yamashita, S. Taniyasu, A. Ogata, and M. Furuuchi. 2017. “Particle size specific distribution of perfluoro alkyl substances in atmospheric particulate matter in Asian cities.” Environmental Science: Processes & Impacts 19 (4):549-560. https://doi.org/10.1039/C6EM00564K.

Gebbink, Wouter A., Urs Berger, and Ian T. Cousins. 2015. “Estimating human exposure to PFOS isomers and PFCA homologues: The relative importance of direct and indirect (precursor) exposure.” Environment International 74:160-169. https://doi.org/10.1016/j.envint.2014.10.013.

Gebbink, Wouter A., Anders Bignert, and Urs Berger. 2016. “Perfluoroalkyl Acids (PFAAs) and Selected Precursors in the Baltic Sea Environment: Do Precursors Play a Role in Food Web Accumulation of PFAAs?” Environmental Science & Technology 50 (12):6354-6362. https://doi.org/10.1021/acs.est.6b01197.

Gefell, Michael J., Hai Huang, Dan Opdyke, Kyle Gustafson, Dimitri Vlassopoulos, John E. McCray, Sam Best, and Minna Carey. 2022. “Modeling PFAS Fate and Transport in Groundwater, with and Without Precursor Transformation.” Groundwater 60 (1):6-14. https://doi.org/10.1111/gwat.13152.

Gellrich, Vanessa, Hubertus Brunn, and Thorsten Stahl. 2013. “Perfluoroalkyl and polyfluoroalkyl substances (PFASs) in mineral water and tap water.” Journal of Environmental Science and Health, Part A 48 (2):129-135. https://doi.org/10.1080/10934529.2013.719431.

Gellrich, V., T. Stahl, and T. P. Knepper. 2012. “Behavior of perfluorinated compounds in soils during leaching experiments.” Chemosphere 87 (9):1052-1056. https://doi.org/10.1016/j.chemosphere.2012.02.011.

Genualdi, Susan, Jessica Beekman, Katherine Carlos, Christine M. Fisher, Wendy Young, Lowri DeJager, and Timothy Begley. 2021. “Analysis of per- and poly-fluoroalkyl substances (PFAS) in processed foods from FDA’s Total Diet Study.” Analytical and Bioanalytical Chemistry. 10.1007/s00216-021-03610-2.

Gerber, Brian J., and Grant W. Neeley. 2005. “Perceived Risk and Citizen Preferences for Governmental Management of Routine Hazards.” Policy Studies Journal 33 (3):395-418. https://doi.org/10.1111/j.1541-0072.2005.00122.x.

German Environment Agency. 2016. HBM I Values for Perfluorooctanoic acid (PFOA) and Perfluorooctanesulfonic acid (PFOS) in blood plasma. Statement of the German Human Biomonitoring Commission (HBM Commission).

German Federal Environment Agency. 2013. Environmentally Responsible Use of Fluorinated Fire-Fighting Foams. https://www.umweltbundesamt.de/en.

German Human Biomonitoring Commission. 2018. “[HBM-I values for Perfluorooctanoic acid (PFOA) and Perfluorooctanesulfonic acid (PFOS) in blood plasma – Statement of the German Human Biomonitoring Commission (HBM Commission)].” Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz 61 (4):474-487. https://doi.org/10.1007/s00103-018-2709-z.

Getzinger, Gordon J., Christopher P. Higgins, and P. Lee Ferguson. 2021. “Structure Database and In Silico Spectral Library for Comprehensive Suspect Screening of Per- and Polyfluoroalkyl Substances (PFASs) in Environmental Media by High-resolution Mass Spectrometry.” Analytical Chemistry 93 (5):2820-2827. https://doi.org/10.1021/acs.analchem.0c04109.

Gewurtz, Sarah B., Satyendra P. Bhavsar, Patrick W. Crozier, Miriam L. Diamond, Paul A. Helm, Chris H. Marvin, and Eric J. Reiner. 2009. “Perfluoroalkyl Contaminants in Window Film: Indoor/Outdoor, Urban/Rural, and Winter/Summer Contamination and Assessment of Carpet as a Possible Source.” Environmental Science & Technology 43 (19):7317-7323. https://doi.org/10.1021/es9002718.

Gewurtz, Sarah B., Satyendra P. Bhavsar, Steve Petro, Chris G. Mahon, Xiaoming Zhao, Dave Morse, Eric J. Reiner, Sheryl A. Tittlemier, Eric Braekevelt, and Ken Drouillard. 2014. “High levels of perfluoroalkyl acids in sport fish species downstream of a firefighting training facility at Hamilton International Airport, Ontario, Canada.” Environment International 67:1-11. https://doi.org/10.1016/j.envint.2014.02.005.

Gewurtz, Sarah B., Lisa E. Bradley, Sean Backus, Alice Dove, Daryl McGoldrick, Hayley Hung, and Helena Dryfhout-Clark. 2019. “Perfluoroalkyl Acids in Great Lakes Precipitation and Surface Water (2006–2018) Indicate Response to Phase-outs, Regulatory Action, and Variability in Fate and Transport Processes.” Environmental Science & Technology 53 (15):8543-8552. https://doi.org/10.1021/acs.est.9b01337.

Ghisi, Rossella, Teofilo Vamerali, and Sergio Manzetti. 2019. “Accumulation of perfluorinated alkyl substances (PFAS) in agricultural plants: A review.” Environmental Research 169:326-341. https://doi.org/10.1016/j.envres.2018.10.023.

Gibbons, J. Whitfield, David E. Scott, Travis J. Ryan, Kurt A. Buhlmann, Tracey D. Tuberville, Brian S. Metts, Judith L. Greene, Tony Mills, Yale Leiden, Sean Poppy, and Christopher T. Winne. 2000. “The Global Decline of Reptiles, Déjà Vu Amphibians: Reptile species are declining on a global scale. Six significant threats to reptile populations are habitat loss and degradation, introduced invasive species, environmental pollution, disease, unsustainable use, and global climate change.” BioScience 50 (8):653-666. 10.1641/0006-3568(2000)050[0653:TGDORD]2.0.CO;2.

Gibbs, S., S. Hong, W. Graves, C. Granville, B. Jayaram, C.R. Blystone, V. C. Robinson, and C. Smith. 2012. “Toxicokinetics of perfluorodecanoic acid (PFDA) after a single intravenous or gavage administration to Harlan Sprague Dawley rats.” The Toxicologist, Supplement to Toxicological Sciences, San Francisco, CA #1875. www.toxsci.oxfordjournals.org.

Giesy, John P., and Kurunthachalam Kannan. 2001. “Global Distribution of Perfluorooctane Sulfonate in Wildlife.” Environmental Science & Technology 35 (7):1339-1342. https://doi.org/10.1021/es001834k.

Giesy, John P., and Kurunthachalam Kannan. 2002. “Peer Reviewed: Perfluorochemical Surfactants in the Environment.” Environmental Science & Technology 36 (7):146A-152A. 10.1021/es022253t.

Giesy, J. P., S.A Mabury, J. W. Martin, K. Kannan, P. D. Jones, J. L. Newsted, and K. Coady. 2006. “Perfluorinated Compounds in the Great Lakes.” In Persistent Organic Pollutants in the Great Lakes, edited by R.A. Hite, 391-438. Vol. 5N, The Handbook of Environmental Chemistry. Berlin, Heidelberg: Springer. ISBN No. 978-3-540-32990-9.

Giesy, J. P., J. Naile, J. Seong Khim, P. D. Jones, and J. L. Newsted. 2010. “Aquatic Toxicology of Perfluorinated Chemicals.” In Reviews of Environmental Contamination and Toxicology, edited by D.M. Whitacre. Vol. 202. Springer Science+Business Media. ISBN No. 978-1-4419-1157-5.

Giffard, Nathan G., Saige A. Gitlin, Marta Rardin, Jonathan M. Petali, Celia Y. Chen, and Megan E. Romano. 2022. “Occurrence and Risks of Per- and Polyfluoroalkyl Substances in Shellfish.” Current Environmental Health Reports 9 (4):591-603. 10.1007/s40572-022-00379-z.

Gilliland, F. D., and J. S. Mandel. 1993. “Mortality among employees of a perfluorooctanoic acid production plant.” J Occup Med 35 (9):950-4.

Giovanoulis, Georgios, Minh Anh Nguyen, Maria Arwidsson, Sarka Langer, Robin Vestergren, and Anne Lagerqvist. 2019. “Reduction of hazardous chemicals in Swedish preschool dust through article substitution actions.” Environment International 130:104921. https://doi.org/10.1016/j.envint.2019.104921.

Gipe, R. L., and H. B. Peterson. 1972. Proportioning Characteristics of Aqueous Film-Forming Foam Concentrates. NRL Report 7437. Washington, D.C.

Giri, Rabindra, Hiroaki Ozaki, T. Morigaki, Shogo Taniguchi, and R. Takanami. 2011. “UV photolysis of perfluorooctanoic acid (PFOA) in dilute aqueous solution.” Water Science and Technology 63 (2):276-282. https://doi.org/10.2166/wst.2011.050.

Giri, Rabindra Raj, Hiroaki Ozaki, Tatsuya Okada, Shogo Taniguchi, and Ryohei Takanami. 2012. “Factors influencing UV photodecomposition of perfluorooctanoic acid in water.” Chemical Engineering Journal 180:197-203. https://doi.org/10.1016/j.cej.2011.11.049.

Gleason, J. A., G. B. Post, and J. A. Fagliano. 2015. “Associations of perfluorinated chemical serum concentrations and biomarkers of liver function and uric acid in the US population (NHANES), 2007-2010.” Environ Res 136:8-14. https://doi.org/10.1016/j.envres.2014.10.004.

Global PFAS Science Panel. 2020. “Global PFAS Science Panel.” accessed 2020. https://www.pfassciencepanel.org.

Globe. 2017. “Basic Turnout Gear Care.” http://globeturnoutgear.com/education/care-and-cleaning/basic-turnout-gear-care-and-cleaning

Glover, C.M., O. Quiñones, and E.R. Dickenson. 2018. “Removal of perfluoroalkyl and polyfluoroalkyl substances in potable reuse systems.” Water Research 144:454-461.

Glüge, Juliane, Rachel London, Ian T. Cousins, Jamie DeWitt, Gretta Goldenman, Dorte Herzke, Rainer Lohmann, Mark

Miller, Carla A. Ng, Sharyle Patton, Xenia Trier, Zhanyun Wang, and Martin Scheringer. 2022. "Information Requirements under the Essential-Use Concept: PFAS Case Studies." Environmental Science & Technology 56 (10):6232-6242. 10.1021/acs.est.1c03732.

Glüge, Juliane, Martin Scheringer, Ian T. Cousins, Jamie C. DeWitt, Gretta Goldenman, Dorte Herzke, Rainer Lohmann, Carla A. Ng, Xenia Trier, and Zhanyun Wang. 2020. "An overview of the uses of per- and polyfluoroalkyl substances (PFAS)." Environmental Science: Processes & Impacts 22 (12):2345-2373. https://doi.org/10.1039/D0EM00291G.

Gobas, F., B. Kelly, and J. Kim. 2020. A Framework for Assessing Bioaccumulation and Exposure Risks of Per- and Polyfluoroalkyl Substances in Threatened and Endangered Species on Aqueous Film Forming Foam (AFFF)-Impacted Sites. ER18-1502: SERDP-ESTCP. https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/ER18-1502.

Gobas, Frank A. P. C., Yung-Shan Lee, Justin C. Lo, Thomas F. Parkerton, and Daniel J. Letinski. 2020. "A Toxicokinetic Framework and Analysis Tool for Interpreting Organisation for Economic Co-operation and Development Guideline 305 Dietary Bioaccumulation Tests." Environmental Toxicology and Chemistry 39 (1):171-188. https://doi.org/10.1002/etc.4599.

Gobelius, L. 2016. Uptake of Per- and Polyfluoroalkyl Substances by Plants. Master's Thesis. Swedish University of Agricultural Sciences.

Gobelius, Laura, Jeffrey Lewis, and Lutz Ahrens. 2017. "Plant Uptake of Per- and Polyfluoroalkyl Substances at a Contaminated Fire Training Facility to Evaluate the Phytoremediation Potential of Various Plant Species." Environmental Science & Technology 51 (21):12602-12610. https://doi.org/10.1021/acs.est.7b02926.

Godlewska, Klaudia, Piotr Stepnowski, and Monika Paszkiewicz. 2020. "Application of the Polar Organic Chemical Integrative Sampler for Isolation of Environmental Micropollutants – A Review." Critical Reviews in Analytical Chemistry 50 (1):1-28. 10.1080/10408347.2019.1565983.

Goeden, Helen M., Christopher W. Greene, and James A. Jacobus. 2019. "A transgenerational toxicokinetic model and its use in derivation of Minnesota PFOA water guidance." Journal of Exposure Science & Environmental Epidemiology 29 (2):183-195. https://doi.org/10.1038/s41370-018-0110-5.

Goeritz, Ina, Sandy Falk, Thorsten Stahl, Christoph Schäfers, and Christian Schlechtriem. 2013. "Biomagnification and tissue distribution of perfluoroalkyl substances (PFASs) in market-size rainbow trout (Oncorhynchus mykiss)." Environmental Toxicology and Chemistry 32 (9):2078-2088. https://doi.org/10.1002/etc.2279.

Goldenberg, M., and Krishna R. Reddy. 2014. "Sustainability Assessment of Excavation and Disposal versus In Situ Stabilization of Heavy Metal-Contaminated Soil at a Superfund Site in Illinois." Geo-Congress 2014, Atlanta, Georgia https://ascelibrary.org/doi/10.1061/9780784413272.219.

Goldenthal, E.I. 1978. Final report. Ninety-day subacute rhesus monkey toxicity study. International Research and Development Corporation. Study No. 137-090. USEPA AR226-0447 (Cited in USEPA, DWQI, 2017a).

Gole, Vitthal L., Reyes Sierra-Alvarez, Hui Peng, John P. Giesy, Pierre Deymier, and Manish Keswani. 2018. "Sono-chemical treatment of per- and poly-fluoroalkyl compounds in aqueous film-forming foams by use of a large-scale multi-transducer dual-frequency based acoustic reactor." Ultrasonics Sonochemistry 45:213-222. https://doi.org/10.1016/j.ultsonch.2018.02.014.

Gomez-Ruiz, Beatriz, Sonia Gómez-Lavín, Nazely Diban, Virginie Boiteux, Adeline Colin, Xavier Dauchy, and Ane Urtiaga. 2017. "Efficient electrochemical degradation of poly- and perfluoroalkyl substances (PFASs) from the effluents of an industrial wastewater treatment plant." Chemical Engineering Journal 322:196-204. https://doi.org/10.1016/j.cej.2017.04.040.

Gomez-Ruiz, Beatriz, Paula Ribao, Nazely Diban, Maria J. Rivero, Inmaculada Ortiz, and Ane Urtiaga. 2018. "Photocatalytic degradation and mineralization of perfluorooctanoic acid (PFOA) using a composite $TiO2$ −rGO catalyst." Journal of Hazardous Materials 344:950-957. https://doi.org/10.1016/j.jhazmat.2017.11.048.

Gomis, M. I., R. Vestergren, D. Borg, and I. T. Cousins. 2018. "Comparing the toxic potency in vivo of long-chain perfluoroalkyl acids and fluorinated alternatives." Environ Int 113:1-9. 10.1016/j.envint.2018.01.011.

Gomis, Melissa I., Robin Vestergren, Helena Nilsson, and Ian T. Cousins. 2016. “Contribution of Direct and Indirect Exposure to Human Serum Concentrations of Perfluorooctanoic Acid in an Occupationally Exposed Group of Ski Waxers.” Environmental Science & Technology 50 (13):7037-7046. 10.1021/acs.est.6b01477.

Gong, Xinying, Ke Li, Chenlu Wu, Lei Wang, and Hongwen Sun. 2018. “Passive sampling for monitoring polar organic pollutants in water by three typical samplers.” Trends in Environmental Analytical Chemistry 17:23-33. https://doi.org/10.1016/j.teac.2018.01.002.

Goodrow, Sandra M., Bruce Ruppel, Robert L. Lippincott, Gloria B. Post, and Nicholas A. Procopio. 2020. “Investigation of levels of perfluoroalkyl substances in surface water, sediment and fish tissue in New Jersey, USA.” Science of The Total Environment 729:138839. https://doi.org/10.1016/j.scitotenv.2020.138839.

Goodrum, Philip E., Janet K. Anderson, Anthony L. Luz, and Graham K. Ansell. 2021. “Application of a Framework for Grouping and Mixtures Toxicity Assessment of PFAS: A Closer Examination of Dose-Additivity Approaches.” Toxicological Sciences 179 (2):262-278. https://doi.org/10.1093/toxsci/kfaa123.

Goosey, Emma, and Stuart Harrad. 2012. “Perfluoroalkyl substances in UK indoor and outdoor air: Spatial and seasonal variation, and implications for human exposure.” Environment International 45:86-90. https://doi.org/10.1016/j.envint.2012.04.007.

Gordon, Steven C. 2011. “Toxicological evaluation of ammonium 4,8-dioxa-3H-perfluorononanoate, a new emulsifier to replace ammonium perfluorooctanoate in fluoropolymer manufacturing.” Regulatory Toxicology and Pharmacology 59 (1):64-80. https://doi.org/10.1016/j.yrtph.2010.09.008.

Goss, Kai-Uwe. 2008. “The pKa Values of PFOA and Other Highly Fluorinated Carboxylic Acids.” Environmental Science & Technology 42 (2):456-458. https://doi.org/10.1021/es702192c.

Goss, Kai-Uwe, Guido Bronner, Tom Harner, Monika Hertel, and Torsten C. Schmidt. 2006. “The Partition Behavior of Fluorotelomer Alcohols and Olefins.” Environmental Science & Technology 40 (11):3572-3577. 10.1021/es060004p.

Gottschall, N., E. Topp, M. Edwards, M. Payne, S. Kleywegt, and D.R. Lapen. 2017. “Brominated flame retardants and perfluoroalkyl acids in groundwater, tile drainage, soil and crop grain following a high application of municipal biosolids to a field.” Science of The Total Environment 574:1345-1359.

Government of Canada. 2005. Addressing psychosocial factors through capacity building: A guide for managers of contaminated sites. Her majesty the Queen in Right of Canada Minister of Health. http://publications.gc.ca/collections/collection_2013/sc-hc/H46-2-05-430-eng.pdf

Government of Canada. 2018. Consultation Document on Proposed Amendments to the Prohibition of Certain Toxic Substances Regulations, 2012 for PFOS, PFOA, LC-PFCAs, HBCD, PBDEs, DP and DBDPE. https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/proposed-amendments-certain-toxic-substances-2018-consultation.html.

Government of Western Australia. 2016. Interim Guideline on the Assessment and Management of Perfluoroalkyl and Polyfluoralkyl Substances (PFAS), Contaminated Sites Guidelines. Department of Environmental Regulation. https://www.der.wa.gov.au/images/documents/your-environment/contaminated-sites/guidelines/Guideline-on-Assessment-and-Management-of-PFAS-.pdf

Grasty, R. C., J. A. Bjork, K. B. Wallace, D. C. Wolf, C. S. Lau, and J. M. Rogers. 2005. “Effects of prenatal perfluorooctane sulfonate (PFOS) exposure on lung maturation in the perinatal rat.” Birth Defects Res B Dev Reprod Toxicol 74 (5):405-16. 10.1002/bdrb.20059.

Grasty, R. C., D. C. Wolf, B. E. Grey, C. S. Lau, and J. M. Rogers. 2003. “Prenatal window of susceptibility to perfluorooctane sulfonate-induced neonatal mortality in the Sprague-Dawley rat.” Birth Defects Res B Dev Reprod Toxicol 68 (6):465-71. 10.1002/bdrb.10046.

Greaves, Alana K., and Robert J. Letcher. 2013. “Linear and branched perfluorooctane sulfonate (PFOS) isomer patterns differ among several tissues and blood of polar bears.” Chemosphere 93 (3):574-580. https://doi.org/10.1016/j.chemosphere.2013.07.013.

Gremmel, Christoph, Tobias Frömel, and Thomas P. Knepper. 2016. “Systematic determination of perfluoroalkyl and polyfluoroalkyl substances (PFASs) in outdoor jackets.” Chemosphere 160:173-180. https://doi.org/10.1016/j.chemosphere.2016.06.043.

Grice, Mira M., Bruce H. Alexander, Richard Hoffbeck, and Diane M. Kampa. 2007. “Self-Reported Medical Conditions in Perfluorooctanesulfonyl Fluoride Manufacturing Workers.” Journal of Occupational and Environmental Medicine 49 (7).

Grieco, S., and R. Edwards. 2019. “Thermal desorption to treat PFAS-contaminated soil.” CRC Care Clean-up, Adelaide, South Australia, Sept. 8-12.

Grieco, S. A., J. Chang, Elizabeth (Lily) Y. Maio, and M. Hwang. 2021. “Comparing conventional and emerging adsorbents for per- and polyfluoroalkyl substances: Kinetic, equilibrium, and column experiments.” AWWA Water Science e1256. https://doi.org/10.1002/aws2.1256.

Griffith, F.D., and J.E. Long. 1980. “Animal toxicity studies with ammonium perfluorooctanoate.” Am. Ind. Hyg. Assoc. J. 41:576-583.

Groffen, Thimo, Robin Lasters, Ana Lopez-Antia, Els Prinsen, Lieven Bervoets, and Marcel Eens. 2019. “Limited reproductive impairment in a passerine bird species exposed along a perfluoroalkyl acid (PFAA) pollution gradient.” Science of The Total Environment 652:718-728. https://doi.org/10.1016/j.scitotenv.2018.10.273.

Gronnestad, R., G. D. Villanger, A. Polder, K. M. Kovacs, C. Lydersen, B. M. Jenssen, and K. Borga. 2017. “Maternal transfer of perfluoroalkyl substances in hooded seals.” Environmental Toxicology and Chemistry 36 (3):763-770. https://doi.org/10.1002/etc.3623.

Gu, Yurong, Wenyi Dong, Cheng Luo, and Tongzhou Liu. 2016. “Efficient Reductive Decomposition of Perfluorooctanesulfonate in a High Photon Flux UV/Sulfite System.” Environmental Science & Technology 50 (19):10554-10561. 10.1021/acs.est.6b03261.

Guelfo, J. 2017. “Development of a user-friendly framework for geospatial identification of potential PFAS source zones.” Brown University, Last Modified June 12. accessed 2021. https://slideplayer.com/slide/12136707/.

Guelfo, Jennifer, L., Thomas Marlow, M. Klein David, A. Savitz David, Scott Frickel, Michelle Crimi, and M. Suuberg Eric. 2018. “Evaluation and Management Strategies for Per- and Polyfluoroalkyl Substances (PFASs) in Drinking Water Aquifers: Perspectives from Impacted U.S. Northeast Communities.” Environmental Health Perspectives 126 (6):065001. https://doi.org/10.1289/EHP2727.

Guelfo, Jennifer L., and David T. Adamson. 2018. “Evaluation of a national data set for insights into sources, composition, and concentrations of per- and polyfluoroalkyl substances (PFASs) in U.S. drinking water.” Environmental Pollution 236:505-513. https://doi.org/10.1016/j.envpol.2018.01.066.

Guelfo, J. L., and C. P. Higgins. 2013. “Subsurface Transport Potential of Perfluoroalkyl Acids at Aqueous Film-Forming Foam (AFFF)-Impacted Sites.” Environmental Science & Technology 47 (9):4164-4171. https://doi.org/10.1021/es3048043.

Guelfo, Jennifer L., Stephen Korzeniowski, Marc A. Mills, Janet Anderson, Richard H. Anderson, Jennifer A. Arblaster, Jason M. Conder, Ian T. Cousins, Kavitha Dasu, Barbara J. Henry, Linda S. Lee, Jinxia Liu, Erica R. McKenzie, and Janice Willey. 2021. “Environmental Sources, Chemistry, Fate and Transport of Per- and Polyfluoroalkyl Substances: State of the Science, Key Knowledge Gaps, and Recommendations Presented at the August 2019 SETAC Focus Topic Meeting.” Environmental Toxicology and Chemistry n/a (n/a). https://doi.org/10.1002/etc.5182.

Guelfo, Jennifer L., Assaf Wunsch, John McCray, John F. Stults, and Christopher P. Higgins. 2020. “Subsurface transport potential of perfluoroalkyl acids (PFAAs): Column experiments and modeling.” Journal of Contaminant Hydrology 233:103661. https://doi.org/10.1016/j.jconhyd.2020.103661.

Gui, Duan, Mei Zhang, Tao Zhang, Bo Zhang, Wenzhi Lin, Xian Sun, Xinjian Yu, Wen Liu, and Yuping Wu. 2019. “Bioaccumulation behavior and spatiotemporal trends of per- and polyfluoroalkyl substances in Indo-Pacific humpback dolphins from the Pearl River Estuary, China.” Science of The Total Environment 658:1029-1038. https://doi.org/10.1016/j.scitotenv.2018.12.278.

Gülsever, G., and H. Parlak. 2018. “Effects of Perfluorooctane Sulfonate Compounds on the Biochemical Activities in Mussels (Mytilus galloprovincialis).” Ege Journal of Fisheries and Aquatic Sciences 35 (4):417-422. https://doi.org/10.12714/egejfas.2018.35.4.07.

Guo, Bo, Jicai Zeng, and Mark L. Brusseau. 2020. “A Mathematical Model for the Release, Transport, and Retention of Per- and Polyfluoroalkyl Substances (PFAS) in the Vadose Zone.” Water Resources Research 56 (2):e2019WR026667. https://doi.org/10.1029/2019WR026667.

Guo, Bo, Jicai Zeng, Mark L. Brusseau, and Yonggen Zhang. 2022. “A screening model for quantifying PFAS leaching in the vadose zone and mass discharge to groundwater.” Advances in Water Resources 160:104102. https://doi.org/10.1016/j.advwatres.2021.104102.

Guo, Hua, Jinghua Wang, Jingzhi Yao, Sujie Sun, Nan Sheng, Xiaowen Zhang, Xuejiang Guo, Yong Guo, Yan Sun, and Jiayin Dai. 2019. “Comparative Hepatotoxicity of Novel PFOA Alternatives (Perfluoropolyether Carboxylic Acids) on Male Mice.” Environmental Science & Technology 53 (7):3929-3937. 10.1021/acs.est.9b00148.

Guo, Wei, Shouliang Huo, Jinglan Feng, and Xiaofei Lu. 2017. “Adsorption of perfluorooctane sulfonate (PFOS) on corn straw-derived biochar prepared at different pyrolytic temperatures.” Journal of the Taiwan Institute of Chemical Engineers 78:265-271. https://doi.org/10.1016/j.jtice.2017.06.013.

Guo, Z., X. Liu, K. Krebs, and N. Roache. 2009. Perfluorocarboxylic Acid Content in 116 Articles of Commerce. Research Triangle Park, NC: National Risk Management Research Laboratory Office of Research and Development.

Gust, K., N. Vinas, M. Wilbanks, E. Mylroie, C. Cox, A. Kimble, K. Jensen, R. Erickson, G. Ankley, J. Conder, and D. Moore. 2021. “Multigenerational PFOS Exposure in Zebrafish (Danio rerio).” Presentation at the Tri-Service Toxicology Consortium (TSTC) Meeting, February.

Gustafsson, Åsa, Åke Bergman, and Jana M. Weiss. 2022. “Estimated daily intake of per- and polyfluoroalkyl substances related to different particle size fractions of house dust.” Chemosphere 303:135061. https://doi.org/10.1016/j.chemosphere.2022.135061.

Gyllenhammar, Irina, Urs Berger, Maria Sundström, Philip McCleaf, Karin Eurén, Sara Eriksson, Sven Ahlgren, Sanna Lignell, Marie Aune, Natalia Kotova, and Anders Glynn. 2015. “Influence of contaminated drinking water on perfluoroalkyl acid levels in human serum – A case study from Uppsala, Sweden.” Environmental Research 140:673-683. https://doi.org/10.1016/j.envres.2015.05.019.

Hadley, Paul W., Ravi Arulanantham, and Deepa Gandhi. 2015. “Yardsticks to Integrate Risk Assessment, Risk Management, and Groundwater Remediation.” Remediation Journal 25:9-30. 10.1002/rem.21430.

Hale, J. R. 2016. “Distribution of PFOS in Groundwater from AFFF Storage, Handling, and Use.” NGWA Groundwater Solutions: Innovating to Address Emerging Issues in Groundwater Resources Symposium.

Hamid, H., and L. Y. Li. 2016. “Role of wastewater treatment plant (WWTP) in environmental cycling of poly- and perfluoroalkyl (PFAS) compounds.” Ecocycles 2:43-53. 10.19040/ecocycles.v2i2.62.

Hamid, H., L. Y. Li, and J. R. Grace. 2018. “Review of the fate and transformation of per- and polyfluoroalkyl substances (PFASs) in landfills.” Environmental Pollution 235:74-84. 10.1016/j.envpol.2017.12.030.

Hammarstrand, S., K. Jakobsson, E. Andersson, Y. Xu, Y. Li, M. Olovsson, and E. M. Andersson. 2021. “Perfluoroalkyl substances (PFAS) in drinking water and risk for polycystic ovarian syndrome, uterine leiomyoma, and endometriosis: A Swedish cohort study.” Environ Int 157:106819. 10.1016/j.envint.2021.106819.

Hammel, Emily, Thomas F. Webster, Rich Gurney, and Wendy Heiger-Bernays. 2022. “Implications of PFAS definitions using fluorinated pharmaceuticals.” iScience 25 (4):104020. https://doi.org/10.1016/j.isci.2022.104020.

Han, Huawen, Muhammad Khalid Rafiq, Tuoyu Zhou, Rong Xu, Ondřej Mašek, and Xiangkai Li. 2019. “A critical review of clay-based composites with enhanced adsorption performance for metal and organic pollutants.” Journal of Hazardous Materials 369:780-796. https://doi.org/10.1016/j.jhazmat.2019.02.003.

Han, H., T.A. Snow, R.A. Kemper, and G.W. Jepson. 2003. “Binding of perfluorooctanoic acid to rat and human plasma proteins.” Chemical Research in Toxicology 16 (6):775-781. https://doi.org/10.1021/tx034005w.

Han, Yuling, Vivek Francis Pulikkal, and Mei Sun. 2021. “Comprehensive Validation of the Adsorbable Organic Fluorine Analysis and Performance Comparison of Current Methods for Total Per- and Polyfluoroalkyl Substances in Water Samples.” ACS ES&T Water 1 (6):1474-1482. 10.1021/acsestwater.1c00047.

Hance, B.J., C. Chess, and P.M. Sandman. 1991. Improving Dialogue with Communities: A Risk Communication Manual for Government. New Jersey Department of Environmental Protection Division of Science and Research.

Hansen, K. J., H. O. Johnson, J. S. Eldridge, J. L. Butenhoff, and L. A. Dick. 2002. “Quantitative Characterization of Trace Levels of PFOS and PFOA in the Tennessee River.” Environmental Science & Technology 36 (8):1681-1685. https://doi.org/10.1021/es010780r.

Hanson, M.L., P.K. Sibley, R.A. Brain, S.A. Mabury, and K.R. Solomon. 2005. “Microcosm Evaluation of the Toxicity and Risk to Aquatic Macrophytes from Perfluorooctane Sulfonic Acid.” Archives of Environmental Contamination and Toxicology 48:329-337. https://doi.org/10.1007/s00244-004-0043-y.

Hao, Feifei, Weilin Guo, Anqi Wang, Yanqiu Leng, and Helian Li. 2014. “Intensification of sonochemical degradation of ammonium perfluorooctanoate by persulfate oxidant.” Ultrasonics Sonochemistry 21 (2):554-558. https://doi.org/10.1016/j.ultsonch.2013.09.016.

Hao, Shilai, Youn-Jeong Choi, Boran Wu, Christopher P. Higgins, Rula Deeb, and Timothy J. Strathmann. 2021. “Hydrothermal Alkaline Treatment for Destruction of Per- and Polyfluoroalkyl Substances in Aqueous Film-Forming Foam.” Environmental Science & Technology 55 (5):3283-3295. 10.1021/acs.est.0c06906.

Hao, Shilai, Youn Jeong Choi, Rula A. Deeb, Timothy J. Strathmann, and Christopher P. Higgins. 2022. “Application of Hydrothermal Alkaline Treatment for Destruction of Per- and Polyfluoroalkyl Substances in Contaminated Groundwater and Soil.” Environmental Science & Technology 56 (10):6647-6657. 10.1021/acs.est.2c00654.

Harada, K. H., and A. Koizumi. 2009. “Environmental and biological monitoring of persistent fluorinated compounds in Japan and their toxicities.” Environ Health Prev Med 14 (1):7-19. https://doi.org/10.1007/s12199-008-0058-5.

Harclerode, Melissa, Sarah Baryluk, Heather Lanza, and John Frangos. 2021. “Preparing for effective, adaptive risk communication about per- and polyfluoroalkyl substances in drinking water.” AWWA Water Science 3 (5):e1236. https://doi.org/10.1002/aws2.1236.

Harclerode, Melissa, Tamzen Macbeth, Michael Miller, Christopher J. Gurr, and Teri S. Myers. 2016. “Early decision framework for integrating sustainable risk management for complex remediation sites: Drivers, barriers, and performance metrics.” Journal of Environmental Management 184 (15):57-66. https://doi.org/10.1016/j.jenvman.2016.07.087.

Harclerode, Melissa, Reanne Ridsdale, D. Darmendrail, Paul Bardos, Filip Alexandrescu, Paul Nathanail, Lisa Pizzol, and Erika Rizzo. 2015. “Integrating the Social Dimension in Remediation Decision-Making: State of the Practice and Way Forward.” Remediation Journal 26:11-42. https://doi.org/10.1002/rem.21447.

Harclerode, Melissa A., Pankaj Lal, Neeraj Vedwan, Bernabas Wolde, and Michael E. Miller. 2016. “Evaluation of the role of risk perception in stakeholder engagement to prevent lead exposure in an urban setting.” Journal of Environmental Management 184:132-142. https://doi.org/10.1016/j.jenvman.2016.07.045.

Harding-Marjanovic, Katie C., Erika F. Houtz, Shan Yi, Jennifer A. Field, David L. Sedlak, and Lisa Alvarez-Cohen. 2015. “Aerobic Biotransformation of Fluorotelomer Thioether Amido Sulfonate (Lodyne) in AFFF-Amended Microcosms.” Environmental Science & Technology 49 (13):7666-7674. https://doi.org/10.1021/acs.est.5b01219.

Harding-Marjanovic, Katie C., Shan Yi, Tess S. Weathers, Jonathan O. Sharp, David L. Sedlak, and Lisa Alvarez-Cohen. 2016. “Effects of Aqueous Film-Forming Foams (AFFFs) on Trichloroethene (TCE) Dechlorination by a Dehalococcoides mccartyi-Containing Microbial Community.” Environmental Science & Technology 50 (7):3352-3361. 10.1021/acs.est.5b04773.

Hardy, J. 1997. “Biological effects of chemicals in the sea-surface microlayer.” In The Sea Surface and Global Change, edited by P. Liss and R. Duce, 339-370. Cambridge: Cambridge University Press. ISBN No. 9780511525025.

Harris, M. W., and L. S. Birnbaum. 1989. “Developmental toxicity of perfluorodecanoic acid in C57BL/6N mice.” Fundam Appl Toxicol 12 (3):442-448. https://doi.org/10.1016/0272-0590(89)90018-3.

Harris, M. W., L. C. Uraih, and L. S. Birnbaum. 1989. “Acute toxicity of perfluorodecanoic acid in C57BL/6 mice differs from 2,3,7,8-tetrachlorodibenzo-p-dioxin.” Fundam Appl Toxicol 13 (4):723-736. https://doi.org/10.1016/0272-0590(89)90330-8.

Hartten, Andrew S. 2014. Water Treatment of PFOA and PFOS. http://www.epa.gov/oppt/pfoa/pubs/Water%20Treatment%20Methods%20Hartten%20Oct16-09.pdf.

Hartwig, K., D. Calleson, and M. Williams. 2006. Unit 1: Community-Based Participatory Research: Getting Grounded. The Examining Community-Institutional Partnerships for Prevention.

Hasegawa, Takeshi. 2015. “Understanding of the intrinsic difference between normal- and perfluoro-alkyl compounds toward total understanding of material properties.” Chemical Physics Letters 627:64-66. https://doi.org/10.1016/j.cplett.2015.03.046.

Hasegawa, Takeshi. 2017. “Physicochemical Nature of Perfluoroalkyl Compounds Induced by Fluorine.” The Chemical Record 17 (10):903-917. https://doi.org/10.1002/tcr.201700018.

Hatton, Jim, Chase Holton, and Bill DiGuiseppi. 2018. “Occurrence and behavior of per- and polyfluoroalkyl substances from aqueous film-forming foam in groundwater systems.” Remediation Journal 28 (2):89-99. https://doi.org/10.1002/rem.21552.

Haug, L. S., S. Huber, G. Becher, and C. Thomsen. 2011. “Characterisation of human exposure pathways to perfluorinated compounds–comparing exposure estimates with biomarkers of exposure.” Environ Int 37 (4):687-93. https://doi.org/10.1016/j.envint.2011.01.011.

Haukås, Marianne, Urs Berger, Haakon Hop, Bjørn Gulliksen, and Geir W. Gabrielsen. 2007. “Bioaccumulation of per- and polyfluorinated alkyl substances (PFAS) in selected species from the Barents Sea food web.” Environmental Pollution 148 (1):360-371. https://doi.org/10.1016/j.envpol.2006.09.021.

Hayashi, Ryuichi, Hayato Obo, Nozomi Takeuchi, and Koichi Yasuoka. 2015. “Decomposition of Perfluorinated Compounds in Water by DC Plasma within Oxygen Bubbles.” Electrical Engineering in Japan 190 (3):9-16. 10.1002/eej.22499.

Hayman, Nicholas T., Gunther Rosen, Marienne A. Colvin, Jason Conder, and Jennifer A. Arblaster. 2021. “Aquatic toxicity evaluations of PFOS and PFOA for five standard marine endpoints.” Chemosphere 273:129699. https://doi.org/10.1016/j.chemosphere.2021.129699.

Hazelton, Peter, W. Cope, Tamara Pandolfo, Shad Mosher, Mark Strynar, Miles Barnhart, and Robert Bringolf. 2012. “Partial life-cycle and acute toxicity of perfluoroalkyl acids to freshwater mussels.” Environmental toxicology and chemistry / SETAC 31:1611-1620. https://doi.org/10.1002/etc.1866.

He, H. P., J. G. Guo, X. D. Xie, and J. L. Peng. 2001. “Location and migration of cations in Cu2+-adsorbed montmorillonite.” Environment International 26 (5):347-352. https://doi.org/10.1016/S0160-4120(01)00011-3.

He, W., M. Megharaj, and R. Naidu. 2016. “Toxicity of perfluorooctanoic acid towards earthworm and enzymatic activities in soil.” Environ Monit Assess 188 (7):424. 10.1007/s10661-016-5416-y.

Health Canada. 2023. Draft objective for per- and polyfluoroalkyl substances in Canadian drinking water: Overview. https://www.canada.ca/en/health-canada/programs/consultation-draft-objective-per-polyfluoroalkyl-substances-canadian-drinking-water/overview.html.

Hekster, Floris, Remi Laane, and Pim De Voogt. 2003. “Environmental and Toxicity Effects of Perfluoroalkylated Substances.” In Reviews of Environmental Contamination and Toxicology, edited by G. Ware, 99-121. Vol. 179. New York, NY: Springer-Verlag. ISBN No. 978-0-387-21731-4.

Hellsing, Maja S., Sarah Josefsson, Arwel V. Hughes, and Lutz Ahrens. 2016. “Sorption of perfluoroalkyl substances to two types of minerals.” Chemosphere 159:385-391. https://doi.org/10.1016/j.chemosphere.2016.06.016.

Helmenstine, A.M. 2018. ” Hydroxyl Group Definition in Chemistry.” ThoughtCo, Last Modified Dec. 5, 2018, Accessed 9-28-19. https://www.thoughtco.com/definition-of-hydroxyl-group-608739.

Helmenstine, A.M. 2019. “Moiety Definition in Chemistry.” ThoughtCo, Accessed 10-5-2019. https://www.thoughtco.com/definition-of-moiety-605357.

Helmer, Ross W., Donald M. Reeves, and Daniel P. Cassidy. 2022. “Per- and Polyfluorinated Alkyl Substances (PFAS) cycling within Michigan: Contaminated sites, landfills and wastewater treatment plants.” Water Research 210:117983. https://doi.org/10.1016/j.watres.2021.117983.

Hemat, H., M. Wilhelm, W. Volkel, C. Mosch, H. Fromme, and J. Wittsiepe. 2010. “Low serum levels of perfluorooctanoic acid (PFOA), perfluorooctane sulfonate (PFOS) and perfluorohexane sulfonate (PFHxS) in children and adults from Afghanistan.” Sci Total Environ 408 (16):3493-5. https://doi.org/10.1016/j.scitotenv.2010.04.040.

Henry, Barbara J., Joseph P. Carlin, Jon A. Hammerschmidt, Robert Buck, L. William Buxton, Heidelore Fiedler, Jennifer Seed, and Oscar Hernandez. 2018. “A Critical Review of the Application of Polymer of Low Concern and Regulatory Criteria to Fluoropolymers.” Integrated Environmental Assessment and Management 14 (3):316-334. https://doi.org/10.1002/ieam.4035.

HEPA. 2018. PFAS National Environmental Management Plan. Heads of EPAs Australia and New Zealand.

HEPA. 2020. PFAS National Environmental Management Plan Version 2.0. Heads of EPA Australia and New Zealand. Australian Government Department of the Environment and Energy (DoEE).

Herrick, Robert L., Jeanette Buckholz, Frank M. Biro, Antonia M. Calafat, Xiaoyun Ye, Changchun Xie, and Susan M. Pinney. 2017. “Polyfluoroalkyl substance exposure in the Mid-Ohio River Valley, 1991–2012.” Environmental Pollution 228:50-60. https://doi.org/10.1016/j.envpol.2017.04.092.

Herzke, Dorte, Elisabeth Olsson, and Stefan Posner. 2012. “Perfluoroalkyl and polyfluoroalkyl substances (PFASs) in consumer products in Norway – A pilot study.” Chemosphere 88 (8):980-987. https://doi.org/10.1016/j.chemosphere.2012.03.035.

Herzke, Dorte, Stefan Posner, and Elisabeth Olsson. 2009. Survey, Screening and Analysis of PFC in consumer products. Project report 09/47: Swerea IVF.

Hickman Jr., H. L. 1999. A Brief History of Solid Waste Management in the US During the Last 50 Years. www.mswmanagement.com.

Higgins, C. 2017. Accumulation of Perfluoroalkyl Acids in Food Crops Webinar. www.sixclasses.org.

Higgins, C. P., L. Alvarez-Cohen, J. A. Field, and C. E. Schaefer. 2021. Final Report. Key Fate and Transport Processes Impacting the Mass Discharge, Attenuation, and Treatment of PFAS and Comingled Chlorinated Solvents or Aromatic Hydrocarbons. SERDP ER-2720 SERDP. https://serdp-estcp-storage.s3.us-gov-west-1.amazonaws.com/s3fs-public/project_documents/ER-2720%2BFinal%2BReport.pdf?VersionId=XWMz1rsYIpSTbwRZzpfdRnuQkGD1I0Ep.

Higgins, Christopher P., Jennifer A. Field, Craig S. Criddle, and Richard G. Luthy. 2005. “Quantitative Determination of Perfluorochemicals in Sediments and Domestic Sludge.” Environmental Science & Technology 39 (11):3946-3956. https://doi.org/10.1021/es048245p.

Higgins, C. P., and R. G. Luthy. 2006. “Sorption of Perfluorinated Surfactants on Sediments.” Environmental Science & Technology 40 (23):7251-7256. https://doi.org/10.1021/es061000n.

Higgins, Christopher P., and Richard G. Luthy. 2007. “Modeling Sorption of Anionic Surfactants onto Sediment Materials: An a priori Approach for Perfluoroalkyl Surfactants and Linear Alkylbenzene Sulfonates.” Environmental Science & Technology 41 (9):3254-3261. https://doi.org/10.1021/es062449j.

Higgins, Christopher P., Pamela B. McLeod, Laura A. MacManus-Spencer, and Richard G. Luthy. 2007. “Bioaccumulation of Perfluorochemicals in Sediments by the Aquatic Oligochaete Lumbriculus variegatus.” Environmental Science & Technology 41 (13):4600-4606. https://doi.org/10.1021/es062792o.

Hill, Philippa J., Mark Taylor, Parikshit Goswami, and Richard S. Blackburn. 2017. “Substitution of PFAS chemistry in outdoor apparel and the impact on repellency performance.” Chemosphere 181:500-507. https://doi.org/10.1016/j.chemosphere.2017.04.122.

Himmelstein, Matthew W., Tessa L. Serex, Robert C. Buck, Jeffrey T. Weinberg, Michael P. Mawn, and Mark H. Russell. 2012. “8:2 fluorotelomer alcohol: A one-day nose-only inhalation toxicokinetic study in the Sprague-Dawley rat with application to risk assessment.” Toxicology 291 (1):122-132. https://doi.org/10.1016/j.tox.2011.11.005.

Hinderliter, P. M. 2003. Perfluorooctanoic Acid: Relationship Between Repeated Inhalation Exposures and Plasma PFOA Concentration in the Rat. Study No. DuPont-12944. Cited in USEPA (2016) – 822-R-16-003.: Haskell Laboratory for Health and Environmental Sciences.

Hinderliter, P. M., M. P. DeLorme, and G. L. Kennedy. 2006. “Perfluorooctanoic acid: relationship between repeated inhalation exposures and plasma PFOA concentration in the rat.” Toxicology 222 (1-2):80-5. https://doi.org/10.1016/j.tox.2006.01.029.

Hoff, P., J. Scheirs, K. Van de Vijver, W. Van Dongen, E. Esmans, R. Blust, and W. De Coen. 2004. “Biochemical effect evaluation of perfluorooctane sulfonic acid-contaminated wood mice (Apodemus sylvaticus).” Environmental Health Perspectives 112 (6):681-686.

Hoffman, K., T. F. Webster, S. M. Bartell, M. G. Weisskopf, T. Fletcher, and V. M. Vieira. 2011. “Private drinking water wells as a source of exposure to perfluorooctanoic acid (PFOA) in communities surrounding a fluoropolymer production facility.” Environ Health Perspect 119 (1):92-7. https://doi.org/10.1289/ehp.1002503.

Hogue, C. 2019. The hunt is on for GenX chemicals in people. 14: Chemical & Engineering News. https://cen.acs.org/environment/persistent-pollutants/hunt-GenX-chemicals-people/97/i14.

Hohenstein, G. 2016. “Overview of Remediation Technologies for PFAS.” Emerging Contaminants Summit, March.

Hoke, Robert A., Barbra D. Ferrell, Tim Ryan, Terry L. Sloman, John W. Green, Diane L. Nabb, Robert Mingoia, Robert C. Buck, and Stephen H. Korzeniowski. 2015. “Aquatic hazard, bioaccumulation and screening risk assessment for 6:2 fluorotelomer sulfonate.” Chemosphere 128:258-265. https://doi.org/10.1016/j.chemosphere.2015.01.033.

Holmquist, H., S. Schellenberger, I. van der Veen, G. M. Peters, P. E. G. Leonards, and I. T. Cousins. 2016. “Properties, performance and associated hazards of state-of-the-art durable water repellent (DWR) chemistry for textile finishing.” Environment International 91:251-264. https://doi.org/10.1016/j.envint.2016.02.035.

Hölzer, Jürgen, Hellmuth Lilienthal, and Michael Schümann. 2021. “Human Biomonitoring (HBM)-I values for perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) – Description, derivation and discussion.” Regulatory Toxicology and Pharmacology 121:104862. https://doi.org/10.1016/j.yrtph.2021.104862.

Hölzer, Jürgen, Oliver Midasch, Knut Rauchfuss, Martin Kraft, Rolf Reupert, Jürgen Angerer, Peter Kleeschulte, Nina Marschall, and Michael Wilhelm. 2008. “Biomonitoring of perfluorinated compounds in children and adults exposed to perfluorooctanoate-contaminated drinking water.” Environmental health perspectives 116 (5):651-657. 10.1289/ehp.11064.

Hong, Seongjin, Jong Seong Khim, Jinsoon Park, Minhee Kim, Woong-Ki Kim, Jinho Jung, Seunghun Hyun, Jeong-Gyu Kim, Hyojin Lee, Heeseon J. Choi, Garry Codling, and John P. Giesy. 2013. “In situ fate and partitioning of waterborne perfluoroalkyl acids (PFAAs) in the Youngsan and Nakdong River Estuaries of South Korea.” Science of The Total Environment 445-446:136-145. https://doi.org/10.1016/j.scitotenv.2012.12.040.

Hoover, Gary, Supratik Kar, Samuel Guffey, Jerzy Leszczynski, and Maria S. Sepúlveda. 2019. “In vitro and in silico modeling of perfluoroalkyl substances mixture toxicity in an amphibian fibroblast cell line.” Chemosphere 233:25-33. https://doi.org/10.1016/j.chemosphere.2019.05.065.

Hopkins, William A. 2000. “Reptile toxicology: Challenges and opportunities on the last frontier in vertebrate ecotoxicology.” Environmental Toxicology and Chemistry 19 (10):2391-2393. https://doi.org/10.1002/etc.5620191001.

Hopkins, Zachary R., Mei Sun, Jamie C. DeWitt, and Detlef R. U. Knappe. 2018. “Recently Detected Drinking Water

Contaminants: GenX and Other Per- and Polyfluoroalkyl Ether Acids." Journal – AWWA 110 (7):13-28. 10.1002/awwa.1073.

Hori, Hisao, Etsuko Hayakawa, Hisahiro Einaga, Shuzo Kutsuna, Kazuhide Koike, Takashi Ibusuki, Hiroshi Kiatagawa, and Ryuichi Arakawa. 2004. "Decomposition of Environmentally Persistent Perfluorooctanoic Acid in Water by Photochemical Approaches." Environmental Science & Technology 38 (22):6118-6124. https://doi.org/10.1021/es049719n.

Hori, Hisao, Misako Murayama, Naoko Inoue, Kyoko Ishida, and Shuzo Kutsuna. 2010. "Efficient mineralization of hydroperfluorocarboxylic acids with persulfate in hot water." Catalysis Today 151 (1):131-136. https://doi.org/10.1016/j.cattod.2010.02.023.

Hori, Hisao, Yumiko Nagaoka, Misako Murayama, and Shuzo Kutsuna. 2008. "Efficient Decomposition of Perfluorocarboxylic Acids and Alternative Fluorochemical Surfactants in Hot Water." Environmental Science & Technology 42 (19):7438-7443. https://doi.org/10.1021/es800832p.

Hori, Hisao, Yumiko Nagaoka, Taizo Sano, and Shuzo Kutsuna. 2008. "Iron-induced decomposition of perfluorohexanesulfonate in sub- and supercritical water." Chemosphere 70 (5):800-806. https://doi.org/10.1016/j.chemosphere.2007.07.015.

Hori, Hisao, Yumiko Nagaoka, Ari Yamamoto, Taizo Sano, Nobuyoshi Yamashita, Sachi Taniyasu, Shuzo Kutsuna, Issey Osaka, and Ryuichi Arakawa. 2006. "Efficient Decomposition of Environmentally Persistent Perfluorooctanesulfonate and Related Fluorochemicals Using Zerovalent Iron in Subcritical Water." Environmental Science & Technology 40 (3):1049-1054. https://doi.org/10.1021/es0517419.

Hori, Hisao, Yuko Takano, Kazuhide Koike, Shuzo Kutsuna, Hisahiro Einaga, and Takashi Ibusuki. 2003. "Photochemical decomposition of pentafluoropropionic acid to fluoride ions with a water-soluble heteropolyacid photocatalyst." Applied Catalysis B: Environmental 46 (2):333-340. https://doi.org/10.1016/S0926-3373(03)00225-X.

Hori, Hisao, Ari Yamamoto, Etsuko Hayakawa, Sachi Taniyasu, Nobuyoshi Yamashita, Shuzo Kutsuna, Hiroshi Kiatagawa, and Ryuichi Arakawa. 2005. "Efficient Decomposition of Environmentally Persistent Perfluorocarboxylic Acids by Use of Persulfate as a Photochemical Oxidant." Environmental Science & Technology 39 (7):2383-2388. 10.1021/es0484754.

Hori, Hisao, Ari Yamamoto, Kazuhide Koike, Shuzo Kutsuna, Issey Osaka, and Ryuichi Arakawa. 2007. "Photochemical decomposition of environmentally persistent short-chain perfluorocarboxylic acids in water mediated by iron(II)/(III) redox reactions." Chemosphere 68 (3):572-578. https://doi.org/10.1016/j.chemosphere.2006.12.038.

Horst, John, Craig Divine, Joe Quinnan, Johnsie Lang, Erika Carter, Theresa Guillette, and Vivek Pulikkal. 2022. "Where Is the PFAS? Innovations in PFAS Detection and Characterization." Groundwater Monitoring & Remediation 42 (1):13-23. https://doi.org/10.1111/gwmr.12502.

Horst, John, Jeff McDonough, Ian Ross, Michael Dickson, Jonathan Miles, Jake Hurst, and Peter Storch. 2018. "Water Treatment Technologies for PFAS: The Next Generation." Groundwater Monitoring & Remediation 38 (2):13-23. https://doi.org/10.1111/gwmr.12281.

Horst, John, Joseph Quinnan, Jeffrey McDonough, Johnsie Lang, Peter Storch, Jeffrey Burdick, and Corey Theriault. 2021. "Transitioning Per- and Polyfluoroalkyl Substance Containing Fire Fighting Foams to New Alternatives: Evolving Methods and Best Practices to Protect the Environment." Groundwater Monitoring & Remediation 41 (2):19-26. https://doi.org/10.1111/gwmr.12444.

Hou, Deyi, Qingbao Gu, Fujun Ma, and Shannon O'Connell. 2016. "Life cycle assessment comparison of thermal desorption and stabilization/solidification of mercury contaminated soil on agricultural land." Journal of Cleaner Production 139:949-956. https://doi.org/10.1016/j.jclepro.2016.08.108.

Houde, Magali, Trevor A. D. Bujas, Jeff Small, Randall S. Wells, Patricia A. Fair, Gregory D. Bossart, Keith R. Solomon, and Derek C. G. Muir. 2006. "Biomagnification of Perfluoroalkyl Compounds in the Bottlenose Dolphin (Tursiops truncatus) Food Web." Environmental Science & Technology 40 (13):4138-4144. 10.1021/es060233b.

Houde, Magali, Gertje Czub, Jeff M. Small, Sean Backus, Xiaowa Wang, Mehran Alaee, and Derek C. G. Muir. 2008.

"Fractionation and Bioaccumulation of Perfluorooctane Sulfonate (PFOS) Isomers in a Lake Ontario Food Web." Environmental Science & Technology 42 (24):9397-9403. 10.1021/es800906r.

Houde, Magali, Amila De Silva, Derek C G Muir, and Robert Letcher. 2011. "Monitoring of Perfluorinated Compounds in Aquatic Biota: An Updated Review PFCs in Aquatic Biota." Environmental Science & Technology 45 (19):7962-7973. https://doi.org/10.1021/es104326w.

Houde, Magali, Mélanie Douville, Maeva Giraudo, Keven Jean, Mélanie Lépine, Christine Spencer, and Amila O. De Silva. 2016. "Endocrine-disruption potential of perfluoroethylcyclohexane sulfonate (PFECHS) in chronically exposed Daphnia magna." Environmental Pollution 218:950-956. https://doi.org/10.1016/j.envpol.2016.08.043.

Houtz, E., Wang M., and J. Park. 2018. "Identification and Fate of Aqueous Film Forming Foam Derived Per- and Polyfluoroalkyl Substances in a Wastewater Treatment Plant." Environmental Science and Technology 52:13212-13221. 10.1021/acs.est.8b04028.

Houtz, Erika F., Christopher P. Higgins, Jennifer A. Field, and David L. Sedlak. 2013. "Persistence of Perfluoroalkyl Acid Precursors in AFFF-Impacted Groundwater and Soil." Environmental Science & Technology 47 (15):8187-8195. http://dx.doi.org/10.1021/es4018877.

Houtz, Erika F., and David L. Sedlak. 2012. "Oxidative Conversion as a Means of Detecting Precursors to Perfluoroalkyl Acids in Urban Runoff." Environmental Science & Technology 46 (17):9342-9349. 10.1021/es302274g.

Houtz, Erika F., Rebecca Sutton, June-Soo Park, and Margaret Sedlak. 2016. "Poly- and perfluoroalkyl substances in wastewater: Significance of unknown precursors, manufacturing shifts, and likely AFFF impacts." Water Research 95:142-149. https://doi.org/10.1016/j.watres.2016.02.055.

Howard, Philip H., and Derek C. G. Muir. 2010. "Identifying New Persistent and Bioaccumulative Organics Among Chemicals in Commerce." Environmental Science & Technology 44 (7):2277-2285. https://doi.org/10.1021/es903383a.

Hu, Xiao-Zhong, and De-Cong Hu. 2009. "Effects of perfluorooctanoate and perfluorooctane sulfonate exposure on hepatoma Hep G2 cells." Archives of Toxicology 83 (9):851-861. 10.1007/s00204-009-0441-z.

Hu, Xindi C., David Q. Andrews, Andrew B. Lindstrom, Thomas A. Bruton, Laurel A. Schaider, Philippe Grandjean, Rainer Lohmann, Courtney C. Carignan, Arlene Blum, Simona A. Balan, Christopher P. Higgins, and Elsie M. Sunderland. 2016. "Detection of Poly- and Perfluoroalkyl Substances (PFASs) in U.S. Drinking Water Linked to Industrial Sites, Military Fire Training Areas, and Wastewater Treatment Plants." Environmental Science & Technology Letters 3 (10):344-350. 10.1021/acs.estlett.6b00260.

Hu, Xindi C., Clifton Dassuncao, Xianming Zhang, Philippe Grandjean, Pál Weihe, Glenys M. Webster, Flemming Nielsen, and Elsie M. Sunderland. 2018. "Can profiles of poly- and Perfluoroalkyl substances (PFASs) in human serum provide information on major exposure sources?" Environmental Health 17 (1):11. 10.1186/s12940-018-0355-4.

Hu, Xindi C., Beverly Ge, Bridger J. Ruyle, Jennifer Sun, and Elsie M. Sunderland. 2021. "A Statistical Approach for Identifying Private Wells Susceptible to Perfluoroalkyl Substances (PFAS) Contamination." Environmental Science & Technology Letters 8 (7):596-602. 10.1021/acs.estlett.1c00264.

Huang, Jiye, Xi Wang, Zhaoqi Pan, Xukai Li, Yu Ling, and Laisheng Li. 2016. "Efficient degradation of perfluorooctanoic acid (PFOA) by photocatalytic ozonation." Chemical Engineering Journal 296:329-334. https://doi.org/10.1016/j.cej.2016.03.116.

Huang, M. C., V. G. Robinson, S. Waidyanatha, A. L. Dzierlenga, M. J. DeVito, M. A. Eifrid, S. T. Gibbs, and C. R. Blystone. 2019. "Toxicokinetics of 8:2 fluorotelomer alcohol (8:2-FTOH) in male and female Hsd:Sprague Dawley SD rats after intravenous and gavage administration." Toxicology Reports 6:924-932. https://doi.org/10.1016/j.toxrep.2019.08.009.

Huang, Shan, and Peter R. Jaffé. 2019. "Defluorination of Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonate (PFOS) by Acidimicrobium sp. Strain A6." Environmental Science & Technology 53 (19):11410-11419. https://doi.org/10.1021/acs.est.9b04047.

Huang, Shan, Matthew Sima, Ying Long, Courtney Messenger, and Peter R. Jaffé. 2022. “Anaerobic degradation of perfluorooctanoic acid (PFOA) in biosolids by Acidimicrobium sp. strain A6.” Journal of hazardous materials 424:127699. https://doi.org/10.1016/j.jhazmat.2021.127699.

Huckins, J.N., J.D. Petty, and K. Booij. 2006. Monitors of Organic Chemicals in the Environment: Semipermeable Membrane Devices: Springer US. ISBN No. 9780387354149.

Hurley, M. D., M. P. Sulbaek Andersen, T. J. Wallington, D. A. Ellis, J. W. Martin, and S. A. Mabury. 2004. “Atmospheric Chemistry of Perfluorinated Carboxylic Acids: Reaction with OH Radicals and Atmospheric Lifetimes.” The Journal of Physical Chemistry A 108 (4):615-620. 10.1021/jp036343b.

Huset, Carin A., Morton A. Barlaz, Douglas F. Barofsky, and Jennifer A. Field. 2011. “Quantitative determination of fluorochemicals in municipal landfill leachates.” Chemosphere 82 (10):1380-1386. https://doi.org/10.1016/j.chemosphere.2010.11.072.

Hwang, M., and S. Grieco. 2021. Orange County Water District PFAS Treatment Testing Study Final Report (Jacobs). https://www.ocwd.com/media/9831/ocwd_pfas_treatment_testing_study_final_report.pdf.

IAP2. 2020. “Core Values for Public Participation.” International Association for Public Participation. https://www.iap2.org/page/corevalues.

IAPP. 2006. “Planning for Effective Public Participation.” https://www.iap2.org/mpage/Home.

IARC. 2016. Some Chemicals Used as Solvents and in Polymer Manufacture. IARC Monographs on the Evaluation of Carcinogenic Risk to Humans. Volume 110. World Health Organization. http://monographs.iarc.fr/ENG/Monographs/vol110/mono110.pdf

IARC. 2023. “Meeting 135 Perfluorooctanoic acid (PFOA) and Perfluorooctanesulfonic acid (PFOS) is announced.” World Health Organization. International Agency for Research on Cancer. https://monographs.iarc.who.int/news-events/meeting-135-perfluorooctanoic-acid-pfoa-and-perfluorooctanesulfonic-acid-pfos-is-announced/.

IDQTF. 2005. Uniform Federal Policy for Quality Assurance Project Plans. Evaluating, Assessing, and Documenting Environmental Data Collection and Use Programs. Part 1: UFP-QAPP Manual. Final, Version 1, March 2005. EPA: EPA-505-B-04-900A, DoD: DTIC ADA 427785.

Imbrigiotta, T.E., and P.T. Harte. 2020. Passive sampling of groundwater wells for determination of water chemistry. No. 1-D8: U.S. Geological Survey.

Institute of Medicine. 2013. Environmental Decisions in the Face of Uncertainty. Washington, D.C.: The National Academies Press. https://doi.org/10.17226/12568.

Inyang, Mandu, and Eric R. V. Dickenson. 2017. “The use of carbon adsorbents for the removal of perfluoroalkyl acids from potable reuse systems.” Chemosphere 184:168-175. https://doi.org/10.1016/j.chemosphere.2017.05.161.

IPCS/OECD. 2004. IPCS Risk Assessment Terminology. Geneva. https://www.who.int/publications/i/item/9241562676.

IPEN. 2018. POPRC-14, White Paper, Fluorine-free firefighting foams (F3) – Viable alternatives to fluorinated aqueous film-forming foams (AFFF).

IPEN. 2019. The Global PFAS Problem: Fluorine-Free Alternatives ans Solutions Firefighting Foams and Other Sources – Going Fluorine-Free. Geneva: IPEN Expert Panel. https://ipen.org/sites/default/files/documents/global_pfas_exec-sum_en.pdf.

Isch, Arnaud, Denis Montenach, Frederic Hammel, Philippe Ackerer, and Yves Coquet. 2019. A Comparative Study of Water and Bromide Transport in a Bare Loam Soil Using Lysimeters and Field Plots. Water 11 (6). 10.3390/w11061199.

ISO. 2009. Technical Committee (TC) 147, Water quality – Determination of perfluorooctansulfonate (PFOS) and perfluorooctanoate (PFOA) – Method for unfiltered samples using solid phase extraction and liquid ISO 25101:2009.

ISO. 2017. Soil Quality – Sustainable Remediation. ISO18504:2017. https://www.iso.org/standard/62688.html.

ITRC. 2003. An Introduction to Characterizing Sites Contaminated with DNAPLs. Washington, D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance

ITRC. 2005. Examination of Risk-Based Screening Values and Approaches of Selected States. RISK-1. Washington, D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2005. Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater, 2nd Edition. ISCO-2: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2007. Protocol for Use of Five Passive Samplers to Sample for a Variety of Contaminants in Groundwater. DSP-5. Washington, D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2008. Enhanced Attenuation: Chlorinated Organics. EACO-1. Washington D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2010. A Decision Framework for Applying Monitored Natural Attenuation Processes to Metals and Radionuclides in Groundwater. APMR-1. Washington, D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2010. Use and Measurement of Mass Flux and Mass Discharge MASSFLUX-1. Washington, D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2011. Project Risk Management for Site Remediation. RRM-1. Washington, DC: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2011. Green and Sustainable Remediation: State of the Science and Practice. . GSR-1. Washington, DC: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2011. Green and Sustainable Remediation: A Practical Framework. GSR-2: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2011. Development of Performance Specifications for Solidification/Stabilization. S/S-1. Washington, DC: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2011. Permeable Reactive Barrier: Technology Update. Washington, DC: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2012. Using Remediation Risk Management to Address Groundwater Cleanup Challenges at Complex Sites. RRM-2. Washington, DC: Interstate Technology &Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2013. Groundwater Statistics and Monitoring Compliance, Statistical Tools for the Project Life Cycle. GSMC-1. Washington, DC: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2015. Integrated DNAPL Site Characterization and Tools Selection. ISC-1. Washington, DC: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2015. Decision Making at Contaminated Sites: Issues and Options in Human Health Risk Assessment. RISK-3. Washington, D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2016. Geospatial Analysis for Optimization at Environmental Sites. GRO-1. Washington, D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2018. LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies. LNAPL-3. Washington, D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance

ITRC. 2018. Stormwater Best Management Practices Performance Evaluation. Washington D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2018. TPH Risk Evaluation at Petroleum-Contaminated Sites. TPHRisk-1. Washington, D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

ITRC. 2019. Implementing Advanced Site Characterization Tools. ASCT-1. Washington, D.C.: Interstate Technology & Regulatory Council. https://itrcweb.org/guidance.

Iwai, H. 2011. “Toxicokinetics of ammonium perfluorohexanoate.” Drug Chem Toxicol 34 (4):341-6. 10.3109/01480545.2011.585162.

Iwai, H., and A. M. Hoberman. 2014. “Oral (Gavage) Combined Developmental and Perinatal/Postnatal Reproduction Toxicity Study of Ammonium Salt of Perfluorinated Hexanoic Acid in Mice.” Int J Toxicol 33 (3):219-237. 10.1177/1091581814529449.

Izadpanah, Amir, and Asghar Javidnia. 2012. “The Ability of a Nanofiltration Membrane to Remove Hardness and Ions from Diluted Seawater.” Water 4 (2):283-294. https://doi.org/10.3390/w4020283.

Jahnke, Annika, Jonathan L. Barber, Kevin C. Jones, and Christian Temme. 2009. “Quantitative trace analysis of polyfluorinated alkyl substances (PFAS) in ambient air samples from Mace Head (Ireland): A method intercomparison.” Atmospheric Environment 43 (4):844-850. https://doi.org/10.1016/j.atmosenv.2008.10.049.

Jahnke, Annika, Urs Berger, Ralf Ebinghaus, and Christian Temme. 2007. “Latitudinal Gradient of Airborne Polyfluorinated Alkyl Substances in the Marine Atmosphere between Germany and South Africa (53° N−33° S).” Environmental Science & Technology 41 (9):3055-3061. https://doi.org/10.1021/es062389h.

Jahnke, Annika, Sandra Huber, Christian Temme, Henrik Kylin, and Urs Berger. 2007. “Development and application of a simplified sampling method for volatile polyfluorinated alkyl substances in indoor and environmental air.” Journal of Chromatography A 1164 (1-2):1-9. https://doi.org/10.1016/j.chroma.2007.06.068.

Jama, Y., S. Lindholst, R.R. Andreasen, H.R. Andersen, A. Kokkoli, T. Svendsen, Z. Cai, and Kragelund C. 2020. “PFAS removal from percolate by super critical water oxidation (SCWO).” 14th annual Water Research Conference: Danish Water Forum (DWF), Frederiksberg, Denmark http://www.danishwaterforum.dk/Research/Annual_Meeting_2020/Annual_announcement2020.html.

Janousek, Raphael M., Jens Mayer, and Thomas P. Knepper. 2019. “Is the phase-out of long-chain PFASs measurable as fingerprint in a defined area? Comparison of global PFAS concentrations and a monitoring study performed in Hesse, Germany from 2014 to 2018.” TrAC Trends in Analytical Chemistry 120:115393. https://doi.org/10.1016/j.trac.2019.01.017.

Ji, K., Y. Kim, S. Oh, B. Ahn, H. Jo, and K. Choi. 2008. “Toxicity of perfluorooctane sulfonic acid and perfluorooctanoic acid on freshwater macroinvertebrates (Daphnia magna and Moina macrocopa) and fish (Oryzias latipes).” Environ Toxicol Chem 27 (10):2159-68. 10.1897/07-523.1.

Jiang, Bo, Jingtang Zheng, Shi Qiu, Mingbo Wu, Qinhui Zhang, Zifeng Yan, and Qingzhong Xue. 2014. “Review on electrical discharge plasma technology for wastewater remediation.” Chemical Engineering Journal 236:348-368. https://doi.org/10.1016/j.cej.2013.09.090.

Jiménez-Castañeda, M.E., and D.I. Medina. 2017. “Use of surfactant-modified zeolites and clays for the removal of heavy metals from water.” Water 9 (4):235.

Jin, ChuanFang, YingHua Sun, Ahmed Islam, Yong Qian, and Alan Ducatman. 2011. “Perfluoroalkyl Acids Including Perfluorooctane Sulfonate and Perfluorohexane Sulfonate in Firefighters.” Journal of Occupational and Environmental Medicine 53 (3). https://doi.org/10.1097/JOM.0b013e31820d1314.

Jin, Hangbiao, Shu Lin, Wei Dai, Lingfang Feng, Tao Li, Jianlin Lou, and Quan Zhang. 2020. “Exposure sources of perfluoroalkyl acids and influence of age and gender on concentrations of chlorinated polyfluorinated ether sulfonates in human serum from China.” Environment International 138:105651. https://doi.org/10.1016/j.envint.2020.105651.

Jin, Hangbiao, Lingling Mao, Jiahui Xie, Meirong Zhao, Xiaoxia Bai, Jie Wen, Tao Shen, and Pengfei Wu. 2020. “Poly- and perfluoroalkyl substance concentrations in human breast milk and their associations with postnatal infant growth.” Science of The Total Environment 713:136417. https://doi.org/10.1016/j.scitotenv.2019.136417.

Jin, Hangbiao, Guoqiang Shan, Lingyan Zhu, Hongwen Sun, and Yi Luo. 2018. “Perfluoroalkyl Acids Including Isomers in

Tree Barks from a Chinese Fluorochemical Manufacturing Park: Implication for Airborne Transportation." Environmental Science & Technology 52 (4):2016-2024. https://doi.org/10.1021/acs.est.7b06241.

Jin, Ling, Chuanjia Jiang, and Pengyi Zhang. 2017. "Photochemical decomposition of 1H,1H,2H,2H-perfluorooctane sulfonate (6:2FTS) induced by ferric ions." Journal of Environmental Sciences 51:120-127. https://doi.org/10.1016/j.jes.2016.08.010.

Jin, Ling, and Pengyi Zhang. 2015. "Photochemical decomposition of perfluorooctane sulfonate (PFOS) in an anoxic alkaline solution by 185nm vacuum ultraviolet." Chemical Engineering Journal 280:241-247. https://doi.org/10.1016/j.cej.2015.06.022.

Jin, Ling, Pengyi Zhang, Tian Shao, and Shiliang Zhao. 2014. "Ferric ion mediated photodecomposition of aqueous perfluorooctane sulfonate (PFOS) under UV irradiation and its mechanism." Journal of Hazardous Materials 271:9-15. https://doi.org/10.1016/j.jhazmat.2014.01.061.

Jing, Ping, Patrick J. Rodgers, and Shigeru Amemiya. 2009. "High Lipophilicity of Perfluoroalkyl Carboxylate and Sulfonate: Implications for Their Membrane Permeability." Journal of the American Chemical Society 131 (6):2290-2296. 10.1021/ja807961s.

Joerss, Hanna, Zhiyong Xie, Charlotte C. Wagner, Wilken-Jon von Appen, Elsie M. Sunderland, and Ralf Ebinghaus. 2020. "Transport of Legacy Perfluoroalkyl Substances and the Replacement Compound HFPO-DA through the Atlantic Gateway to the Arctic Ocean—Is the Arctic a Sink or a Source?" Environmental Science & Technology 54 (16):9958-9967. 10.1021/acs.est.0c00228.

Johansson, Jana H., Urs Berger, and Ian T. Cousins. 2017. "Can the use of deactivated glass fibre filters eliminate sorption artefacts associated with active air sampling of perfluorooctanoic acid?" Environmental Pollution 224:779-786. https://doi.org/10.1016/j.envpol.2017.01.020.

Johansson, J. H., M. E. Salter, J. C. Acosta Navarro, C. Leck, E. D. Nilsson, and I. T. Cousins. 2019. "Global transport of perfluoroalkyl acids via sea spray aerosol." Environmental Science: Processes & Impacts 21 (4):635-649. 10.1039/C8EM00525G.

Johansson, Jana H., Hong Yan, Urs Berger, and Ian T. Cousins. 2017. "Water-to-air transfer of branched and linear PFOA: Influence of pH, concentration and water type." Emerging Contaminants 3 (1):46-53. https://doi.org/10.1016/j.emcon.2017.03.001.

Johansson, Niclas, Per Eriksson, and Henrik Viberg. 2009. "Neonatal exposure to PFOS and PFOA in mice results in changes in proteins which are important for neuronal growth and synaptogenesis in the developing brain." Toxicological sciences : an official journal of the Society of Toxicology 108 2:412-8.

Johansson, N., A. Fredriksson, and P. Eriksson. 2008. "Neonatal exposure to perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) causes neurobehavioural defects in adult mice." Neurotoxicology 29 (1):160-9. 10.1016/j.neuro.2007.10.008.

Johnson, Gwynn R. 2022. "PFAS in soil and groundwater following historical land application of biosolids." Water Research 211:118035. https://doi.org/10.1016/j.watres.2021.118035.

Johnson, G.W., and M.J. Bock. 2014. "Modeled PCB weathering series in principal components space: considerations for multivariate chemical fingerprinting." In Environmental Forensics 117-124. Cambridge, UK: Royal Society of Chemistry. ISBN No.

Johnson, G.W., R. Ehrlich, W. Full, and S. Ramos. 2015. "Principal Components Analysis and Receptor Models in Environmental Forensics." In Introduction to Environmental Forensics, edited by B.L. Murphy and R.D. Morrison. Elsevier. ISBN No. 9780124046962.

Johnson, G.W., J.F. Quensen, J.R. Chiarenzelli, and M.C. Hamilton. 2006. "Polychlorinated Biphenyls." In Environmental Forensics: Contaminant Specific Guide. Burlington, MA: Elsevier-Academic Press. ISBN No. 978-0125077514.

Johnson, J.D., and R. E. Ober. 1979. Absorption of FC-95-14C in rats after a single oral dose. 3M. Submitted to the U.S. Environmental Protection Agency's Administrative Record. AR226-0007. (cited in ATSDR, 2015).

Johnson, James K., Christopher M. Hoffman, Douglas A. Smith, and Zhiyong Xia. 2019. "Advanced Filtration Membranes for the Removal of Perfluoroalkyl Species from Water." ACS Omega 4 (5):8001-8006. 10.1021/acsomega.9b00314.

Johnson, Mark S., Robert C. Buck, Ian T. Cousins, Christopher P. Weis, and Suzanne E. Fenton. 2021. "Estimating Environmental Hazard and Risks from Exposure to Per- and Polyfluoroalkyl Substances (PFASs): Outcome of a SETAC Focused Topic Meeting." Environmental Toxicology and Chemistry 40 (3):543-549. https://doi.org/10.1002/etc.4784.

Johnson, M.S., M.J. Quinn, Jr., M.A. Williams, and A.M. Narizzano. 2021. Understanding Risk to Wildlife from Exposures to Per- and Polyfluorinated Alkyl Substances (PFAS). Oxford, UK: CRC Press, Taylor and Francis. ISBN No. 9781003162476.

Johnson, P. I., P. Sutton, D. S. Atchley, E. Koustas, J. Lam, S. Sen, K. A. Robinson, D. A. Axelrad, and T. J. Woodruff. 2014. "The Navigation Guide – evidence-based medicine meets environmental health: systematic review of human evidence for PFOA effects on fetal growth." Environ Health Perspect 122 (10):1028-39. 10.1289/ehp.1307893.

Johnson, R. L., A. J. Anschutz, J. M. Smolen, M. F. Simcik, and R. L. Penn. 2007. "The Adsorption of Perfluorooctane Sulfonate onto Sand, Clay, and Iron Oxide Surfaces." Journal of Chemical & Engineering Data 52 (4):1165-1170. 10.1021/je060285g.

Jones, Devin K., Kathryn A. Quinlin, Maggie A. Wigren, Youn J. Choi, Maria S. Sepúlveda, Linda S. Lee, David L. Haskins, Guilherme R. Lotufo, Alan Kennedy, Lauren May, Ashley Harmon, Thomas Biber, Nicolas Melby, Michael K. Chanov, Michelle L. Hudson, Peter B. Key, Katy W. Chung, David W. Moore, Jamie G. Suski, Edward F. Wirth, and Jason T. Hoverman. 2022. "Acute Toxicity of Eight Aqueous Film-Forming Foams to 14 Aquatic Species." Environmental Science & Technology 56 (10):6078-6090. 10.1021/acs.est.1c03776.

Jones, Paul D., Wenyue Hu, Wim De Coen, John L. Newsted, and John P. Giesy. 2003. "Binding of perfluorinated fatty acids to serum proteins." Environmental Toxicology and Chemistry 22 (11):2639-2649. 10.1897/02-553.

Joo, S.H., and B. Tansel. 2015. "Novel technologies for reverse osmosis concentrate treatment: a review." Journal of Environmental Management 150:322-335.

Jovicic, Vojislav, Muhammad Khan, Ana Zbogar – Rasic, Nataliia Fedorova, Alexander Poser, Peter Swoboda, and Antonio Delgado. 2018. "Degradation of Low Concentrated Perfluorinated Compounds (PFCs) from Water Samples Using Non-Thermal Atmospheric Plasma (NTAP)." Energies 11. 10.3390/en11051290.

Ju, Xiaodong, Yihe Jin, Kazuaki Sasaki, and Norimitsu Saito. 2008. "Perfluorinated Surfactants in Surface, Subsurface Water and Microlayer from Dalian Coastal Waters in China." Environmental Science & Technology 42 (10):3538-3542. 10.1021/es703006d.

Kabadi, Shruti V., Jeffrey Fisher, Jason Aungst, and Penelope Rice. 2018. "Internal exposure-based pharmacokinetic evaluation of potential for biopersistence of 6:2 fluorotelomer alcohol (FTOH) and its metabolites." Food and Chemical Toxicology 112:375-382. https://doi.org/10.1016/j.fct.2018.01.012.

Kabadi, Shruti V., Jeffrey W. Fisher, Daniel R. Doerge, Darshan Mehta, Jason Aungst, and Penelope Rice. 2020. "Characterizing biopersistence potential of the metabolite 5:3 fluorotelomer carboxylic acid after repeated oral exposure to the 6:2 fluorotelomer alcohol." Toxicology and Applied Pharmacology 388:114878. https://doi.org/10.1016/j.taap.2020.114878.

Kaboré, Hermann A., Sung Vo Duy, Gabriel Munoz, Ladji Méité, Mélanie Desrosiers, Jinxia Liu, Traoré Karim Sory, and Sébastien Sauvé. 2018. "Worldwide drinking water occurrence and levels of newly-identified perfluoroalkyl and polyfluoroalkyl substances." Science of The Total Environment 616-617:1089-1100. https://doi.org/10.1016/j.scitotenv.2017.10.210.

Kaiser, Mary, Barbara Larsen, Barbara Dawson, Kristine Kurtz, Robert Lieckfield, James Miller, and John Flaherty. 2005. "Method for the Determination of Perfluorooctanoic Acid in Air Samples Using Liquid Chromatography with Mass Spectrometry." Journal of occupational and environmental hygiene 2 (6):307-313. https://doi.org/10.1080/15459620590959713.

Kaiser, M. A., C. A. Barton, M. Botelho, R.C. Buck, L. W. Buxton, J. Gannon, C. P. C. Kao, B.S. Larsen, M. H. Russell, N. Wang, and R. L. Waterland. 2006. "Understanding the transport of anthropogenic fluorinated compounds in the environment.” Organohalogen Compd 68:675-678.

Kaiser, Mary A., Barbara Dawson, Catherine Barton, and Miguel Botelho. 2010. “Understanding Potential Exposure Sources of Perfluorinated Carboxylic Acids in the Workplace.” The Annals of Occupational Hygiene 54 (8):915-22. https://doi.org/10.1093/annhyg/meq066.

Kaiser, Mary A., Barbara S. Larsen, Chien-Ping C. Kao, and Robert C. Buck. 2005. “Vapor Pressures of Perfluorooctanoic, -nonanoic, -decanoic, -undecanoic, and -dodecanoic Acids.” Journal of Chemical & Engineering Data 50 (6):1841-1843. https://doi.org/10.1021/je050070r.

Kambala, V.S.R., and R. Naidu. 2013. Amine modified clay sorbents and methods for their use. edited by U.S. Patent and Trademark Office.

Kancharla, Samhitha, Aditya Choudhary, Ryan T. Davis, Dengpan Dong, Dmitry Bedrov, Marina Tsianou, and Paschalis Alexandridis. 2022. “GenX in water: Interactions and self-assembly.” Journal of Hazardous Materials 428:128137. https://doi.org/10.1016/j.jhazmat.2021.128137.

Kannan, Kurunthachalam, Simonetta Corsolini, Jerzy Falandysz, Gilberto Fillmann, Kurunthachalam Senthil Kumar, Bommanna G. Loganathan, Mustafa Ali Mohd, Jesus Olivero, Nathalie Van Wouwe, Jae Ho Yang, and Kenneth M. Aldous. 2004. “Perfluorooctanesulfonate and Related Fluorochemicals in Human Blood from Several Countries.” Environmental Science & Technology 38 (17):4489-4495. 10.1021/es0493446.

Kannan, Kurunthachalam, Emily Perrotta, and Nancy J. Thomas. 2006. “Association between Perfluorinated Compounds and Pathological Conditions in Southern Sea Otters.” Environmental Science & Technology 40 (16):4943-4948. 10.1021/es060932o.

Kannan, Kurunthachalam, Lin Tao, Ewan Sinclair, Stephanie D. Pastva, Dave J. Jude, and John P. Giesy. 2005. “Perfluorinated Compounds in Aquatic Organisms at Various Trophic Levels in a Great Lakes Food Chain.” Archives of Environmental Contamination and Toxicology 48 (4):559-566. 10.1007/s00244-004-0133-x.

Karnjanapiboonwong, Adcharee, Sanjit K. Deb, Seenivasan Subbiah, Degeng Wang, and Todd A. Anderson. 2018. “Perfluoroalkylsulfonic and carboxylic acids in earthworms (Eisenia fetida): Accumulation and effects results from spiked soils at PFAS concentrations bracketing environmental relevance.” Chemosphere 199:168-173. https://doi.org/10.1016/j.chemosphere.2018.02.027.

Karrman, A., K. Elgh-Dalgren, C. Lafossas, and T. Moskeland. 2011. “Environmental levels and distribution of structural isomers of perfluoroalkyl acids after Aqueous Fire-Fighting Foam (AFFF) contamination.” Environmental Chemistry 8:372-380. 10.1071/EN10145.

Kärrman, Anna, Bert van Bavel, Ulf Järnberg, Lennart Hardell, and Gunilla Lindström. 2006. “Perfluorinated chemicals in relation to other persistent organic pollutants in human blood.” Chemosphere 64 (9):1582-1591. https://doi.org/10.1016/j.chemosphere.2005.11.040.

Kaserzon, Sarit L., Karen Kennedy, Darryl W. Hawker, Jack Thompson, Steve Carter, Anthony C. Roach, Kees Booij, and Jochen F. Mueller. 2012. “Development and Calibration of a Passive Sampler for Perfluorinated Alkyl Carboxylates and Sulfonates in Water.” Environmental Science & Technology 46 (9):4985-4993. 10.1021/es300593a.

Kasperson, Roger E., and Jeanne X. Kasperson. 1996. “The Social Amplification and Attenuation of Risk.” The ANNALS of the American Academy of Political and Social Science 545 (1):95-105. 10.1177/0002716296545001010.

Kato, H., S. Fujii, M. Takahashi, M. Matsumoto, M. Hirata-Koizumi, A. Ono, and A. Hirose. 2015. “Repeated dose and reproductive/developmental toxicity of perfluorododecanoic acid in rats.” Environ Toxicol 30 (11):1244-63. 10.1002/tox.21996.

Kato, K., A.A. Kalathil, A. M. Patel, X. Ye, and A.M. Calafat. 2018. “Per- and Polyfluoroalkyl substances and fluorinated alternatives in urine and serum by on-line solid phase extraction-liquid chromatography-tandem mass spectrometry.” Chemosphere 209:338-345.

Kato, K., X. Ye, and A. M. Calafat. 2015. ” PFASs in the General Population.” In Toxicological Effects of Perfluoroalkyl and Polyfluoroalkyl Substances, edited by J.C. DeWitt, 151-176. Humana Press. ISBN No. 978-3-319-15517-3.

Kawabata, K., H. Matsuzaki, S. Nukui, M. Okazaki, A. Sakai, Y. Kawashima, and N. Kudo. 2017. "Perfluorododecanoic Acid Induces Cognitive Deficit in Adult Rats." Toxicol Sci 157 (2):421-428. 10.1093/toxsci/kfx058.

Kawashima, Y., H. Kobayashi, H. Miura, and H. Kozuka. 1995. "Characterization of hepatic responses of rat to administration of perfluorooctanoic and perfluorodecanoic acids at low levels." Toxicology 99 (3):169-78.

Keiter, Su, L. Baumann, H. Färber, H. Holbech, D. Skutlarek, M. Engwall, and T. Braunbeck. 2012. "Long-term effects of a binary mixture of perfluorooctane sulfonate (PFOS) and bisphenol A (BPA) in zebrafish (Danio rerio)." Aquatic Toxicology 118-119:116-129. https://doi.org/10.1016/j.aquatox.2012.04.003.

Kelly, Barry C., Michael G. Ikonomou, Joel D. Blair, Blair Surridge, Dale Hoover, Richard Grace, and Frank A. P. C. Gobas. 2009. "Perfluoroalkyl Contaminants in an Arctic Marine Food Web: Trophic Magnification and Wildlife Exposure." Environmental Science & Technology 43 (11):4037-4043. https://doi.org/10.1021/es9003894.

KEMI. 2004. "Perfluorooctane Sulfonate (PFOS) Dossier Prepared in Support for a Nomination of PFOS to the UN-ECE LRTAP Protocol and the Stockholm Convention." Stockholm Convention, Stockholm, Sweden, August.

KEMI. 2005. Proposal for Listing Perfluorooctane Sulfonate (PFOS) in Annex A of the Stockholm Convention on Persistent Organic Pollutants. Stockholm: Swedish Chemicals Agency.

KEMI. 2015. Chemical analysis of selected fire-fighting foams on the Swedish Market 2014. Stockholm Swedish Chemicals Agency.

KEMI. 2015. Occurrence and Use of Highly Fluorinated Substances and Alternatives. 0284-1185: Swedish Chemicals Agency.

KEMI. 2017. The 16 New POPs. Stockholm: Swedish Chemicals Agency.

Kemper, R. A., and G. W. Jepson. 2003. "Pharmacokinetics of perfluorooctanoic acid in male and female rats." SOT Annual Meeting 716. https://www.toxicology.org/application/ToxicologistDB/index.aspx.

Kempisty, D., Y. Xing, and L. Racz, eds. 2018. Perfluoroalkyl Substances in the Environment: Theory, Practice and innovation, CRC Press: Taylor & Francis Group. New York. ISBN No. 9780429487125.

Kennedy, G. L., Jr., J. L. Butenhoff, G. W. Olsen, J. C. O'Connor, A. M. Seacat, R. G. Perkins, L. B. Biegel, S. R. Murphy, and D. G. Farrar. 2004. "The toxicology of perfluorooctanoate." Crit Rev Toxicol 34 (4):351-84.

Kennedy, G.L., G.T. Hall, M.R. Brittelli, J.R. Barnes, and H.C. Chen. 1986. "Inhalation toxicity of ammonium perfluorooctanoate." Food and Chemical Toxicology (24):1325-1329.

Kerfoot, W. B. 2014. Method and Apparatus for Treating Perfluoroalkyl Compounds. edited by U.S. Patent and Trademark Office.

Kerfoot, W. B. 2016. "Treatment of Emerging Contaminants of Concern with ActivateOzone." Florida Remediation Conference, Orlando, FL, November 30-December 1.

Khalil, K., M. Lee, and K. Steenland. 2015. "Epidemiological Findings." In Toxicological Effects of Perfluoroalkyl and Polyfluoroalkyl Substances, edited by J.D. DeWitt, 305-335. Humana Press. ISBN No. 978-3-319-15517-3.

Khan, M. Yasir, Sui So, and Gabriel da Silva. 2020. "Decomposition kinetics of perfluorinated sulfonic acids." Chemosphere 238:124615. https://doi.org/10.1016/j.chemosphere.2019.124615.

Kibbey, Tohren C. G., Rafal Jabrzemski, and Denis M. O'Carroll. 2020. "Supervised machine learning for source allocation of per- and polyfluoroalkyl substances (PFAS) in environmental samples." Chemosphere 252:126593. https://doi.org/10.1016/j.chemosphere.2020.126593.

Kim Lazcano, Rooney, Youn Jeong Choi, Michael L. Mashtare, and Linda S. Lee. 2020. "Characterizing and Comparing Per- and Polyfluoroalkyl Substances in Commercially Available Biosolid and Organic Non-Biosolid-Based Products." Environmental Science & Technology 54 (14):8640-8648. 10.1021/acs.est.9b07281.

Kim Lazcano, Rooney, Chloé de Perre, Michael L. Mashtare, and Linda S. Lee. 2019. "Per- and polyfluoroalkyl substances in commercially available biosolid-based products: The effect of treatment processes." Water Environment Research 91 (12):1669-1677. https://doi.org/10.1002/wer.1174.

Kim, Minhee, Loretta Y. Li, John R. Grace, and Chaoyang Yue. 2014. "Selecting reliable physicochemical properties of perfluoroalkyl and polyfluoroalkyl substances (PFASs) based on molecular descriptors." Environmental Pollution 196:462-472. https://doi.org/10.1016/j.envpol.2014.11.008.

Kim, Minhee, Loretta Y. Li, John R. Grace, and Chaoyang Yue. 2015. "Selecting reliable physiochemical properties of perfluoroalkyl and polyfluoroalkyl substances (PFASs) based on molecular descriptors." Environmental Pollution 196:462-472.

Kim, Seung-Kyu, and Kurunthachalam Kannan. 2007. "Perfluorinated Acids in Air, Rain, Snow, Surface Runoff, and Lakes: Relative Importance of Pathways to Contamination of Urban Lakes." Environmental Science & Technology 41 (24):8328-8334. https://doi.org/10.1021/es072107t.

Kim, Seung-Kyu, Dong-Hao Li, Mahiba Shoeib, and Kyung-Duk Zoh. 2013. "Contribution of diffuse inputs to the aqueous mass load of perfluoroalkyl acids in river and stream catchments in Korea." Science of The Total Environment 470-471 (1):1430-1440. https://doi.org/10.1016/j.scitotenv.2013.06.040.

Kim, Seung-Kyu, Dong-Hao Li, Mahiba Shoeib, and Kyung-Duk Zoh. 2014. "Contribution of diffuse inputs to the aqueous mass load of perfluoroalkyl acids in river and stream catchments in Korea." Science of The Total Environment 470-471:1430-1440. https://doi.org/10.1016/j.scitotenv.2013.06.040.

Kim, Tae-Hun, Sun-Hong Lee, Hyun Young Kim, Kyle Doudrick, Seungho Yu, and Sang Don Kim. 2019. "Decomposition of perfluorooctane sulfonate (PFOS) using a hybrid process with electron beam and chemical oxidants." Chemical Engineering Journal 361:1363-1370. https://doi.org/10.1016/j.cej.2018.10.195.

Kinney, L. A., N. C. Chromey, and G. L. Kennedy, Jr. 1989. "Acute inhalation toxicity of ammonium perfluorononanoate." Food Chem Toxicol 27 (7):465-8.

Kirchgeorg, Torben, Annekatrin Dreyer, Jacopo Gabrieli, Natalie Kehrwald, Michael Sigl, Margit Schwikowski, Claude Boutron, Andrea Gambaro, Carlo Barbante, and Ralf Ebinghaus. 2013. "Temporal variations of perfluoroalkyl substances and polybrominated diphenyl ethers in alpine snow." Environmental Pollution 178:367-374. https://doi.org/10.1016/j.envpol.2013.03.043.

Kirchgeorg, T., A. Dreyer, P. Gabrielli, J. Gabrieli, L. G. Thompson, C. Barbante, and R. Ebinghaus. 2016. "Seasonal accumulation of persistent organic pollutants on a high altitude glacier in the Eastern Alps." Environmental Pollution 218:804-812. https://doi.org/10.1016/j.envpol.2016.08.004.

Kirk, M., K. Smurthwaite, J. Bräunig, S. Trevenar, C. D'Este, R. Lucas, A. Lal, R. Korda, A. Clements, J. Mueller, and B. Armstrong. 2018. The PFAS Health Study: Systematic Literature Review. Canberra, Australia: Australian National University. https://rsph.anu.edu.au/files/PFAS%20Health%20Study%20Systematic%20Review.pdf

Kirk Pflugh, K., and S. Shannon. 1989. Alternatives to Public Hearing.: New Jersey Department of Environmental Protection.

Kirk Pflugh, K., and S. Shannon. 1992. Improving Public Participation in Environmental Cases: Lessons for Agency Outreach Efforts 1991-1992. New Jersey Department of Environmental Protection.

Kirkpatrick, J. B. 2005. A Combined 28-day Repeated Dose Oral Toxicity Study with the Reproduction/Developmental Toxicity Screening Test of Perfluorohexanoic Acid and 1H, 1H, 2H, 2H-tridecafluoro-1-octanol in Rats, with Recovery. Ashland, OH: LLC WIL Research Laboratories.

Kissa, E. 1994. Fluorinated Surfactants: Synthesis, Properties, Applications. New York, NY: M. Dekker. ISBN No. 9780824790110.

Kissa, E. 2001. Fluorinated Surfactants and Repellents, Second Edition Revised and Expanded. Edited by A. T. Hubbard, Surfactant Science Series. New York, New York: Marcel Dekker, Inc. ISBN No. 0-8247-0472-X.

Kjeldsen, Lisbeth Stigaard, and Eva Cecilie Bonefeld-Jørgensen. 2013. "Perfluorinated compounds affect the function of sex hormone receptors." Environmental Science and Pollution Research 20 (11):8031-8044. https://doi.org/10.1007/s11356-013-1753-3.

Klassen, C.D. 2013. Casarett and Doull's Toxicology: The Basic Science of Poisons. New York, NY: McGraw-Hill Education. ISBN No. 9780071769235.

Klaunig, J. E., M. Shinohara, H. Iwai, C. P. Chengelis, J. B. Kirkpatrick, Z. Wang, and R. H. Bruner. 2015. "Evaluation of the chronic toxicity and carcinogenicity of perfluorohexanoic acid (PFHxA) in Sprague-Dawley rats." Toxicol Pathol 43 (2):209-20. 10.1177/0192623314530532.

Knight, Emma R., Jennifer Bräunig, Leslie J. Janik, Divina A. Navarro, Rai S. Kookana, Jochen F. Mueller, and Michael J. McLaughlin. 2021. "An investigation into the long-term binding and uptake of PFOS, PFOA and PFHxS in soil – plant systems." Journal of Hazardous Materials 404:124065. https://doi.org/10.1016/j.jhazmat.2020.124065.

Knight, Emma R., Leslie J. Janik, Divina A. Navarro, Rai S. Kookana, and Michael J. McLaughlin. 2019. "Predicting partitioning of radiolabelled 14C-PFOA in a range of soils using diffuse reflectance infrared spectroscopy." Science of The Total Environment 686:505-513. https://doi.org/10.1016/j.scitotenv.2019.05.339.

Korzeniowski, Stephen H., Robert C. Buck, Robin M. Newkold, Ahmed El kassmi, Evan Laganis, Yasuhiko Matsuoka, Bertrand Dinelli, Severine Beauchet, Frank Adamsky, Karl Weilandt, Vijay Kumar Soni, Deepak Kapoor, Priyanga Gunasekar, Marco Malvasi, Giulio Brinati, and Stefana Musio. 2023. "A critical review of the application of polymer of low concern regulatory criteria to fluoropolymers II: Fluoroplastics and fluoroelastomers." Integrated Environmental Assessment and Management 19 (2):326-354. https://doi.org/10.1002/ieam.4646.

Kothawala, Dolly N., Stephan J. Köhler, Anna Östlund, Karin Wiberg, and Lutz Ahrens. 2017. "Influence of dissolved organic matter concentration and composition on the removal efficiency of perfluoroalkyl substances (PFASs) during drinking water treatment." Water Research 121:320-328. https://doi.org/10.1016/j.watres.2017.05.047.

Kotlarz, Nadine, James McCord, David Collier, C. Suzanne Lea, Mark Strynar, B. Lindstrom Andrew, A. Wilkie Adrien, Y. Islam Jessica, Katelyn Matney, Phillip Tarte, M. E. Polera, Kemp Burdette, Jamie DeWitt, Katlyn May, C. Smart Robert, R. U. Knappe Detlef, and A. Hoppin Jane. "Measurement of Novel, Drinking Water-Associated PFAS in Blood from Adults and Children in Wilmington, North Carolina." Environmental Health Perspectives 128 (7):077005. 10.1289/EHP6837.

Kotthoff, Matthias, Josef Müller, Heinrich Juerling, Martin Schlummer, and Dominik Fiedler. 2015. "Perfluoroalkyl and polyfluoroalkyl substances in consumer products." Environmental Science and Pollution Research 22:14546-14559. https://doi.org/10.1007/s11356-015-4202-7.

Kovarich, S., E. Papa, J. Li, and P. Gramatica. 2012. "QSAR classification models for the screening of the endocrine-disrupting activity of perfluorinated compounds." SAR and QSAR in Environmental Research 23 (3-4):207-220. https://doi.org/10.1080/1062936X.2012.657235.

Krafft, Marie Pierre, and Jean G. Riess. 2015. "Selected physicochemical aspects of poly- and perfluoroalkylated substances relevant to performance, environment and sustainability—Part one." Chemosphere 129:4-19. https://doi.org/10.1016/j.chemosphere.2014.08.039.

Kramer, H. J., W. A. van den Ham, W. Slob, and M. N. Pieters. 1996. "Conversion Factors Estimating Indicative Chronic No-Observed-Adverse-Effect Levels from Short-Term Toxicity Data." Regulatory Toxicology and Pharmacology 23 (3):249-255. https://doi.org/10.1006/rtph.1996.0050.

Krause Max, J., Eben Thoma, Endalkachew Sahle-Damesessie, Brian Crone, Andrew Whitehill, Erin Shields, and Brian Gullett. 2022. "Supercritical Water Oxidation as an Innovative Technology for PFAS Destruction." Journal of Environmental Engineering 148 (2):05021006. 10.1061/(ASCE)EE.1943-7870.0001957.

Krippner, Johanna, Sandy Falk, Hubertus Brunn, Sebastian Georgii, Sven Schubert, and Thorsten Stahl. 2015. "Accumulation Potentials of Perfluoroalkyl Carboxylic Acids (PFCAs) and Perfluoroalkyl Sulfonic Acids (PFSAs) in Maize (Zea mays)." Journal of Agricultural and Food Chemistry 63 (14):3646-3653. https://doi.org/10.1021/acs.jafc.5b00012.

Krug, Jonathan D., Paul M. Lemieux, Chun-Wai Lee, Jeffrey V. Ryan, Peter H. Kariher, Erin P. Shields, Lindsay C.

Wickersham, Martin K. Denison, Kevin A. Davis, David A. Swensen, R. Preston Burnette, Jost O. L. Wendt, and William P. Linak. 2022. “Combustion of C1 and C2 PFAS: Kinetic modeling and experiments.” Journal of the Air & Waste Management Association 72 (3):256-270. 10.1080/10962247.2021.2021317.

Krusic, Paul J., Alexander A. Marchione, Fredric Davidson, Mary A. Kaiser, Chien-Ping C. Kao, Raymond E. Richardson, Miguel Botelho, Robert L. Waterland, and Robert C. Buck. 2005. “Vapor Pressure and Intramolecular Hydrogen Bonding in Fluorotelomer Alcohols.” The Journal of Physical Chemistry A 109 (28):6232-6241. 10.1021/jp0502961.

Kudo, N. 2015. “Metabolism and Pharmacokinetics.” In Toxicological Effects of Perfluoroalkyl and Polyfluoroalkyl Substances, edited by J. C. DeWitt, 151-76. Humana Press. ISBN No. 978-3-319-15517-3.

Kudo, Naomi, Yuko Iwase, Hiroshi Okayachi, Yoshihiro Yamakawa, and Yoichi Kawashima. 2005. “Induction of Hepatic Peroxisome Proliferation by 8–2 Telomer Alcohol Feeding In Mice: Formation of Perfluorooctanoic Acid in the Liver.” Toxicological Sciences 86 (2):231-238. 10.1093/toxsci/kfi191.

Kudo, N., and Y. Kawashima. 2003. “Induction of triglyceride accumulation in the liver of rats by perfluorinated fatty acids with different carbon chain lengths: comparison with induction of peroxisomal beta-oxidation.” Biol Pharm Bull 26 (1):47-51.

Kudo, N., E. Suzuki-Nakajima, A. Mitsumoto, and Y. Kawashima. 2006. “Responses of the liver to perfluorinated fatty acids with different carbon chain length in male and female mice:in relation to induction of hepatomegaly, peroxisomal beta-oxidation and microsomal 1-acylglycerophosphocholine acyltransferase.” Biol Pharm Bull 29 (9):1952-7.

Kulkarni, Poonam R., David T. Adamson, Jovan Popovic, and Charles J. Newell. 2022. “Modeling a well-characterized perfluorooctane sulfonate (PFOS) source and plume using the REMChlor-MD model to account for matrix diffusion.” Journal of Contaminant Hydrology 247:103986. https://doi.org/10.1016/j.jconhyd.2022.103986.

Kumarasamy, Elango, Irene M. Manning, Leonard B. Collins, Orlando Coronell, and Frank A. Leibfarth. 2020. “Ionic Fluorogels for Remediation of Per- and Polyfluorinated Alkyl Substances from Water.” ACS Central Science 6 (4):487-492. https://doi.org/10.1021/acscentsci.9b01224.

Kupryianchyk, Darya, Sarah E. Hale, Gijs D. Breedveld, and Gerard Cornelissen. 2016. “Treatment of sites contaminated with perfluorinated compounds using biochar amendment.” Chemosphere 142:35-40. https://doi.org/10.1016/j.chemosphere.2015.04.085.

Kuykendall, D. C., and A. McMullan. 2014. “Using an Environmental Footprint Analysis to Evaluate the Sustainability of Remedial Alternatives.” PE International Conference on Health, Safety, and Environment.

Kwadijk, Christiaan, M. J. J. Kotterman, and Albert Koelmans. 2014. “Partitioning of perfluorooctanesulfonate and perfluorohexanesulfonate in the aquatic environment after an accidental release of Aqueous Film Forming Foam at Schiphol Amsterdam Airport.” Environmental Toxicology and Chemistry 33 (8):1761-1765. https://doi.org/10.1002/etc.2602.

Kwadijk, C. J. A. F., P. Korytár, and A. A. Koelmans. 2010. “Distribution of Perfluorinated Compounds in Aquatic Systems in The Netherlands.” Environmental Science & Technology 44 (10):3746-3751. https://doi.org/10.1021/es100485e.

Kwadijk, C. J. A. F., I. Velzeboer, and A. A. Koelmans. 2013. “Sorption of perfluorooctane sulfonate to carbon nanotubes in aquatic sediments.” Chemosphere 90 (5):1631-1636. https://doi.org/10.1016/j.chemosphere.2012.08.041.

Kwan, W. C. 2001. Physical property determination of perfluorinated surfactants. MS Thesis. University of Toronto. http://www.collectionscanada.ca/obj/s4/f2/dsk3/ftp05/MQ62941.pdf.

Kwiatkowski, Carol F., David Q. Andrews, Linda S. Birnbaum, Thomas A. Bruton, Jamie C. DeWitt, Detlef R. U. Knappe, Maricel V. Maffini, Mark F. Miller, Katherine E. Pelch, Anna Reade, Anna Soehl, Xenia Trier, Marta Venier, Charlotte C. Wagner, Zhanyun Wang, and Arlene Blum. 2020. “Scientific Basis for Managing PFAS as a Chemical Class.” Environmental Science & Technology Letters 7 (8):532-543. https://doi.org/10.1021/acs.estlett.0c00255.

Kwiatkowski, Carol F., David Q. Andrews, Linda S. Birnbaum, Thomas A. Bruton, Jamie C. DeWitt, Detlef R. U. Knappe, Maricel V. Maffini, Mark F. Miller, Katherine E. Pelch, Anna Reade, Anna Soehl, Xenia Trier, Marta Venier, Charlotte C.

Wagner, Zhanyun Wang, and Arlene Blum. 2020. “Scientific Basis for Managing PFAS as a Chemical Class.” Environmental Science & Technology Letters 7 (8):532-543. 10.1021/acs.estlett.0c00255.

Kwok, Karen Y., Sachi Taniyasu, Leo W. Y. Yeung, Margaret B. Murphy, Paul K. S. Lam, Yuichi Horii, Kurunthachalam Kannan, Gert Petrick, Ravindra K. Sinha, and Nobuyoshi Yamashita. 2010. “Flux of Perfluorinated Chemicals through Wet Deposition in Japan, the United States, And Several Other Countries.” Environmental Science & Technology 44 (18):7043-7049. 10.1021/es101170c.

Kwok, Karen Y., Eriko Yamazaki, Nobuyoshi Yamashita, Sachi Taniyasu, Margaret B. Murphy, Yuichi Horii, Gert Petrick, Roland Kallerborn, Kurunthachalam Kannan, Kentaro Murano, and Paul K. S. Lam. 2013. “Transport of Perfluoroalkyl substances (PFAS) from an arctic glacier to downstream locations: Implications for sources.” Science of The Total Environment 447:46-55. https://doi.org/10.1016/j.scitotenv.2012.10.091.

Labadie, Pierre, and Marc Chevreuil. 2011. “Partitioning behaviour of perfluorinated alkyl contaminants between water, sediment and fish in the Orge River (nearby Paris, France).” Environmental Pollution 159 (2):391-397. https://doi.org/10.1016/j.envpol.2010.10.039.

Ladics, Gregory S., Gerald L. Kennedy, John O’Connor, Nancy Everds, Linda A. Malley, Steven R. Frame, Shawn Gannon, Reinhard Jung, Thomas Roth, Hiroyuki Iwai, and Seiji Shin-ya. 2008. “90-Day Oral Gavage Toxicity Study of 8-2 Fluorotelomer Alcohol in Rats.” Drug and Chemical Toxicology 31 (2):189-216. 10.1080/01480540701873103.

Lai, Senchao, Junwei Song, Tianli Song, Zhijiong Huang, Yingyi Zhang, Yan Zhao, Guicheng Liu, Junyu Zheng, Wenying Mi, Jianhui Tang, Shichun Zou, Ralf Ebinghaus, and Zhiyong Xie. 2016. “Neutral polyfluoroalkyl substances in the atmosphere over the northern South China Sea.” Environmental Pollution 214:449-455. https://doi.org/10.1016/j.envpol.2016.04.047.

Lam, J., E. Koustas, P. Sutton, P. I. Johnson, D. S. Atchley, S. Sen, K. A. Robinson, D. A. Axelrad, and T. J. Woodruff. 2014. “The Navigation Guide – evidence-based medicine meets environmental health: integration of animal and human evidence for PFOA effects on fetal growth.” Environ Health Perspect 122 (10):1040-51. 10.1289/ehp.1307923.

Lam, James C. W., Jinling Lyu, Karen Y. Kwok, and Paul K. S. Lam. 2016. “Perfluoroalkyl Substances (PFASs) in Marine Mammals from the South China Sea and Their Temporal Changes 2002–2014: Concern for Alternatives of PFOS?” Environmental Science & Technology 50 (13):6728-6736. 10.1021/acs.est.5b06076.

Lamb, Dane T., Kartik Venkatraman, Nanthi Bolan, Nanjappa Ashwath, Girish Choppala, and Ravi Naidu. 2014. “Phytocapping: An Alternative Technology for the Sustainable Management of Landfill Sites.” Critical Reviews in Environmental Science and Technology 44 (6):561-637. 10.1080/10643389.2012.728823.

Lampert, David J. 2018. “Emerging Research Needs for Assessment and Remediation of Sediments Contaminated with Per- and Poly-fluoroalkyl Substances.” Current Pollution Reports 4 (4):277-279. 10.1007/s40726-018-0098-4.

Landsteiner, A., C. Huset, J. Johnson, and A. Williams. 2014. “Biomonitoring for perfluorochemicals in a Minnesota community with known drinking water contamination.” J Environ Health 77 (5):14-9.

Lang, J. R. 2016. Per- and Polyfluoroalkyl Substances in Municipal Solid Waste and Landfill Leachate. Doctoral Dissertation. North Carolina State University, Raleigh, NC. https://repository.lib.ncsu.edu/bitstream/handle/1840.20/33339/etd.pdf?sequence=1.

Lang, Johnsie R., B. McKay Allred, Jennifer A. Field, James W. Levis, and Morton A. Barlaz. 2017. “National Estimate of Per- and Polyfluoroalkyl Substance (PFAS) Release to U.S. Municipal Landfill Leachate.” Environmental Science & Technology 51 (4):2197-2205. http://doi.org/10.1021/acs.est.6b05005.

Lang, Johnsie R., B. McKay Allred, Graham F. Peaslee, Jennifer A. Field, and Morton A. Barlaz. 2016. “Release of Per- and Polyfluoroalkyl Substances (PFASs) from Carpet and Clothing in Model Anaerobic Landfill Reactors.” Environmental Science & Technology 50 (10):5024-5032. 10.1021/acs.est.5b06237.

Lang, Johnsie R., Mark J. Strynar, Andrew B. Lindstrom, Amy Farthing, Hwa Huang, Judith Schmid, Donna Hill, and Neil Chernoff. 2020. “Toxicity of Balb-c mice exposed to recently identified 1,1,2,2-tetrafluoro-2-[1,1,1,2,3,3-hexafluoro-3-(1,1,2,2-tetrafluoroethoxy)propan-2-yl]oxyethane-1-sulfonic acid (PFESA-BP2).” Toxicology 441:152529. https://doi.org/10.1016/j.tox.2020.152529.

Langberg, Håkon A., Gijs D. Breedveld, Gøril Aa Slinde, Hege M. Grønning, Åse Høisæter, Morten Jartun, Thomas Rundberget, Bjørn M. Jenssen, and Sarah E. Hale. 2020. "Fluorinated Precursor Compounds in Sediments as a Source of Perfluorinated Alkyl Acids (PFAA) to Biota." Environmental Science & Technology 54 (20):13077-13089. 10.1021/acs.est.0c04587.

Langberg, Håkon A., Sarah E. Hale, Gijs D. Breedveld, Bjørn M. Jenssen, and Morten Jartun. 2022. "A review of PFAS fingerprints in fish from Norwegian freshwater bodies subject to different source inputs." Environmental Science: Processes & Impacts 24 (2):330-342. 10.1039/D1EM00408E.

Lange, Cleston C. 2018. "Anaerobic biotransformation of N-methyl perfluorobutanesulfonamido ethanol and N-ethyl perfluorooctanesulfonamido ethanol." Environmental Toxicology and Chemistry 37 (3):768-779. 10.1002/etc.4014.

Langer, Vera, Annekatrin Dreyer, and Ralf Ebinghaus. 2010. "Polyfluorinated Compounds in Residential and Nonresidential Indoor Air." Environmental Science & Technology 44 (21):8075-8081. 10.1021/es102384z.

Langley, A. E., and G. D. Pilcher. 1985. "Thyroid, bradycardic and hypothermic effects of perfluoro-n-decanoic acid in rats." J Toxicol Environ Health 15 (3-4):485-91. 10.1080/15287398509530675.

Langlois, Ingrid, Urs Berger, Zdenek Zencak, and Michael Oehme. 2007. "Mass spectral studies of perfluorooctane sulfonate derivatives separated by high-resolution gas chromatography." Rapid Communications in Mass Spectrometry 21 (22):3547-3553. https://doi.org/10.1002/rcm.3241.

Lanza, Heather A., Rebecca S. Cochran, Joseph F. Mudge, Adric D. Olson, Brett R. Blackwell, Jonathan D. Maul, Christopher J. Salice, and Todd A. Anderson. 2017. "Temporal monitoring of perfluorooctane sulfonate accumulation in aquatic biota downstream of historical aqueous film forming foam use areas." Environmental Toxicology and Chemistry 36 (8):2022-2029. http://doi.org/10.1002/etc.3726.

LaRoe, S., J. Benaman, D.R. Opdyke, and J.P. Connolly. 2017. "Emerging concern about PFOS in freshwater fish: how bioaccumulative is it?" Ninth (9th) International Conference on the Remediation and Management of Contaminated Sediments, New Orleans, LA, January 9 – 12, 2017.

Larson, Emily S., Jason M. Conder, and Jennifer A. Arblaster. 2018. "Modeling avian exposures to perfluoroalkyl substances in aquatic habitats impacted by historical aqueous film forming foam releases." Chemosphere 201:335-341. https://doi.org/10.1016/j.chemosphere.2018.03.004.

Lasee, Steven, Kaylin McDermett, Naveen Kumar, Jennifer Guelfo, Paxton Payton, Zhao Yang, and Todd A. Anderson. 2022. "Targeted analysis and Total Oxidizable Precursor assay of several insecticides for PFAS." Journal of Hazardous Materials Letters 3:100067. https://doi.org/10.1016/j.hazl.2022.100067.

Lasier, Peter J., John W. Washington, Sayed M. Hassan, and Thomas M. Jenkins. 2011. "Perfluorinated chemicals in surface waters and sediments from northwest Georgia, USA, and their bioaccumulation in Lumbriculus variegatus." Environmental Toxicology and Chemistry 30 (10):2194-2201. 10.1002/etc.622.

Lassen, C., Allan Jensen, A Potrykus, Frans Christensen, J. Kjølholt, C. Jeppesen, Sonja Mikkelsen, and S. Innanen. 2013. Survey of PFOS, PFOA and other perfluoroalkyl and polyfluoroalkyl substances. Part of the LOUS-Review. Environmental Project No. 1475. Copenhagen.

Lassen, C., J. Kjølholt, Sonja Mikkelsen, M. Warming, Allan Jensen, Rossana Bossi, and I Nielsen. 2015. Polyfluoroalkyl substances (PFASs) in textiles for children: Survey of chemical substances in consumer products. 136. Copenhagen, Denmark: Danish Environmental Protection Agency.

Lath, Supriya, Divina A. Navarro, Dusan Losic, Anupama Kumar, and Michael J. McLaughlin. 2018. "Sorptive remediation of perfluorooctanoic acid (PFOA) using mixed mineral and graphene/carbon-based materials." Environmental Chemistry 15 (8):472-480.

Lau, C. 2012. "Perfluorinated Compounds." In Molecular, Clinical and Environmental Toxicology, edited by A. Luch, 47-86. Vol. Experientia Supplementum, 101. Basel: Springer. ISBN No. 978-3-7643-8340-4.

Lau, C. 2015. "Perfluorinated Compounds: An Overview." In Toxicological Effects of Perfluoroalkyl and Polyfluoroalkyl Substances, edited by J.D. DeWitt. Humana Press. ISBN No. 978-3-319-15517-3.

Lau, Christopher, Katherine Anitole, Colette Hodes, David Lai, Andrea Pfahles-Hutchens, and Jennifer Seed. 2007. “Perfluoroalkyl Acids: A Review of Monitoring and Toxicological Findings.” Toxicological Sciences 99 (2):366-394. https://doi.org/10.1093/toxsci/kfm128.

Lau, C., J. R. Thibodeaux, R. G. Hanson, M. G. Narotsky, J. M. Rogers, A. B. Lindstrom, and M. J. Strynar. 2006. “Effects of perfluorooctanoic acid exposure during pregnancy in the mouse.” Toxicol Sci 90 (2):510-8. 10.1093/toxsci/kfj105.

Lau, C., J. R. Thibodeaux, R. G. Hanson, J. M. Rogers, B. E. Grey, M. E. Stanton, J. L. Butenhoff, and L. A. Stevenson. 2003. “Exposure to perfluorooctane sulfonate during pregnancy in rat and mouse. II: postnatal evaluation.” Toxicol Sci 74 (2):382-92. 10.1093/toxsci/kfg122.

Lau, W. J., A. F. Ismail, N. Misdan, and M. A. Kassim. 2012. “A recent progress in thin film composite membrane: A review.” Desalination 287:190-199. https://doi.org/10.1016/j.desal.2011.04.004.

Lauria, Mélanie Z., Ayman Naim, Merle Plassmann, Jenny Fäldt, Roxana Sühring, and Jonathan P. Benskin. 2022. “Widespread Occurrence of Non-Extractable Fluorine in Artificial Turfs from Stockholm, Sweden.” Environmental Science & Technology Letters 9 (8):666-672. 10.1021/acs.estlett.2c00260.

Le, Song-Thao, Yi Gao, Tohren C. G. Kibbey, William C. Glamore, and Denis M. O’Carroll. 2021. “A new framework for modeling the effect of salt on interfacial adsorption of PFAS in environmental systems.” Science of The Total Environment 796:148893. https://doi.org/10.1016/j.scitotenv.2021.148893.

Le, Thi Xuan Huong, Holly Haflich, Amisha D. Shah, and Brian P. Chaplin. 2019. “Energy-Efficient Electrochemical Oxidation of Perfluoroalkyl Substances Using a Ti4O7 Reactive Electrochemical Membrane Anode.” Environmental Science & Technology Letters 6 (8):504-510. 10.1021/acs.estlett.9b00397.

Lechner, Mareike, and Holger Knapp. 2011. “Carryover of Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonate (PFOS) from Soil to Plant and Distribution to the Different Plant Compartments Studied in Cultures of Carrots (Daucus carota ssp. Sativus), Potatoes (Solanum tuberosum), and Cucumbers (Cucumis Sativus).” Journal of Agricultural and Food Chemistry 59 (20):11011-11018. https://doi.org/10.1021/jf201355y.

Lee, C. K., S. G. Kang, J. T. Lee, S. W. Lee, J. H. Kim, D. H. Kim, B. C. Son, K. H. Kim, C. H. Suh, S. Y. Kim, and Y. B. Park. 2015. “Effects of perfluorooctane sulfuric acid on placental PRL-family hormone production and fetal growth retardation in mice.” Mol Cell Endocrinol 401:165-72. 10.1016/j.mce.2014.10.026.

Lee, Holly, Jessica D’eon, and Scott A. Mabury. 2010. “Biodegradation of Polyfluoroalkyl Phosphates as a Source of Perfluorinated Acids to the Environment.” Environmental Science & Technology 44 (9):3305-3310. 10.1021/es9028183.

Lee, Holly, and Scott A. Mabury. 2011. “A Pilot Survey of Legacy and Current Commercial Fluorinated Chemicals in Human Sera from United States Donors in 2009.” Environmental Science & Technology 45 (19):8067-8074. https://doi.org/10.1021/es200167q.

Lee, Holly, and Scott A. Mabury. 2017. “Sorption of Perfluoroalkyl Phosphonates and Perfluoroalkyl Phosphinates in Soils.” Environmental Science & Technology 51 (6):3197-3205. 10.1021/acs.est.6b04395.

Lee, Holly, Alex G. Tevlin, Scotia A. Mabury, and Scott A. Mabury. 2014. “Fate of Polyfluoroalkyl Phosphate Diesters and Their Metabolites in Biosolids-Applied Soil: Biodegradation and Plant Uptake in Greenhouse and Field Experiments.” Environmental Science & Technology 48 (1):340-349. https://doi.org/10.1021/es403949z.

Lee, I., and H. Viberg. 2013. “A single neonatal exposure to perfluorohexane sulfonate (PFHxS) affects the levels of important neuroproteins in the developing mouse brain.” Neurotoxicology 37:190-6. 10.1016/j.neuro.2013.05.007.

Lee, Jin Wuk, Jae-Woo Lee, Yu-Jin Shin, Ji-Eun Kim, Tae-Kwon Ryu, Jisung Ryu, Jaean Lee, Pilje Kim, Kyunghee Choi, and Kyunghwa Park. 2017. “Multi-generational xenoestrogenic effects of Perfluoroalkyl acids (PFAAs) mixture on Oryzias latipes using a flow-through exposure system.” Chemosphere 169:212-223. https://doi.org/10.1016/j.chemosphere.2016.11.035.

Lee, Yuchi, Shanglien Lo, Jeff Kuo, and Chinghong Hsieh. 2012. “Decomposition of perfluorooctanoic acid by microwaveactivated persulfate: Effects of temperature, pH, and chloride ions.” Frontiers of Environmental Science &

Engineering 6 (1):17-25. 10.1007/s11783-011-0371-x.

Lee, Yu-Chi, Meng-Jia Chen, C. P. Huang, Jeff Kuo, and Shang-Lien Lo. 2016. “Efficient Sonochemical Degradation of Perfluorooctanoic Acid Using Periodate.” Ultrasonics Sonochemistry 31:499-505. https://doi.org/10.1016/j.ultsonch.2016.01.030.

Lee, Yu-Chi, Shang-Lien Lo, Pei-Te Chiueh, and Der-Guang Chang. 2009. “Efficient decomposition of perfluorocarboxylic acids in aqueous solution using microwave-induced persulfate.” Water Research 43 (11):2811-2816. https://doi.org/10.1016/j.watres.2009.03.052.

Lee, Yu-Chi, Shang-Lien Lo, Pei-Te Chiueh, Yau-Hsuan Liou, and Man-Li Chen. 2010. “Microwave-hydrothermal decomposition of perfluorooctanoic acid in water by iron-activated persulfate oxidation.” Water Research 44 (3):886-892. https://doi.org/10.1016/j.watres.2009.09.055.

Lee, Yu-Chi, Shang-Lien Lo, Jeff Kuo, and Yi-Ling Lin. 2012. “Persulfate oxidation of perfluorooctanoic acid under the temperatures of 20–40°C.” Chemical Engineering Journal 198-199:27-32. https://doi.org/10.1016/j.cej.2012.05.073.

Lee, Young-Min, Ji-Young Lee, Moon-Kyung Kim, Heedeuk Yang, Jung-Eun Lee, Yeongjo Son, Younglim Kho, Kyungho Choi, and Kyung-Duk Zoh. 2020. “Concentration and distribution of per- and polyfluoroalkyl substances (PFAS) in the Asan Lake area of South Korea.” Journal of Hazardous Materials 381:120909. https://doi.org/10.1016/j.jhazmat.2019.120909.

Leeson, Andrea, Timothy Thompson, Hans F. Stroo, Richard H. Anderson, Jason Speicher, Marc A. Mills, Janice Willey, Charles Coyle, Rajat Ghosh, Carmen Lebrón, and Cara Patton. 2021. “Identifying and Managing Aqueous Film-Forming Foam-Derived Per- and Polyfluoroalkyl Substances in the Environment.” Environmental Toxicology and Chemistry 40 (1):24-36. https://doi.org/10.1002/etc.4894.

Lei, Yong-Jia, Yu Tian, Zahra Sobhani, Ravi Naidu, and Cheng Fang. 2020. “Synergistic degradation of PFAS in water and soil by dual-frequency ultrasonic activated persulfate.” Chemical Engineering Journal 388:124215. https://doi.org/10.1016/j.cej.2020.124215.

Leidos. 2019. Final Surface Water Study Technical Memorandum for the Perfluorinated Compound Facility Investigation at Horsham Air Guard Station (111th Attack Wing), Horsham, Pennsylvania. https://ar.afcec-cloud.af.mil/585472.pdf?token=TjvK6_EYIppeRMXcBjJhHT9qfgQTd0ycKX4Xlv2Fp841.

LeMasters, Grace K., Ash M. Genaidy, Paul Succop, James Deddens, Tarek Sobeih, Heriberto Barriera-Viruet, Kari Dunning, and James Lockey. 2006. “Cancer Risk Among Firefighters: A Review and Meta-analysis of 32 Studies.” Journal of Occupational and Environmental Medicine 48 (11):1189-1202. https://doi.org/10.1097/01.jom.0000246229.68697.90.

Lemlich, Robert. 1972. Adsorptive Bubble Separation Techniques. First ed: Academic Press. ISBN No. 9780323154819.

Lemlich, Robert, and Elias Lavi. 1961. “Foam Fractionation with Reflux.” Science 134 (3473):191-191. 10.1126/science.134.3473.191.

Lenka, Swadhina Priyadarshini, Melanie Kah, and Lokesh P. Padhye. 2021. “A review of the occurrence, transformation, and removal of poly- and perfluoroalkyl substances (PFAS) in wastewater treatment plants.” Water Research 199:117187. https://doi.org/10.1016/j.watres.2021.117187.

Leonard, R. C. 2003. Epidemiology Surveillance Program. Cancer Incidence Report 1959-2001 and All-Case Mortality Report 1957-2000 at the Washington Works, Parkersburg, WV. DuPont. AR226-1307-6: USEPA.

Lerner, S. 2016. “New Teflon Toxin Causes Cancer in Lab Animals.” The Intercept, Last Modified March 3. accessed 2020. https://theintercept.com/2016/03/03/new-teflon-toxin-causes-cancer-in-lab-animals/.

Lescord, Gretchen L., Karen A. Kidd, Amila O. De Silva, Mary Williamson, Christine Spencer, Xiaowa Wang, and Derek C. G. Muir. 2015. “Perfluorinated and Polyfluorinated Compounds in Lake Food Webs from the Canadian High Arctic.” Environmental Science & Technology 49 (5):2694-2702. https://doi.org/10.1021/es5048649.

Lesmeister, Lukas, Frank Thomas Lange, Jörn Breuer, Annegret Biegel-Engler, Evelyn Giese, and Marco Scheurer. 2021.

"Extending the knowledge about PFAS bioaccumulation factors for agricultural plants – A review." Science of The Total Environment 766:142640. https://doi.org/10.1016/j.scitotenv.2020.142640.

Letcher, R. J., J. O. Bustnes, R. Dietz, B. M. Jenssen, E. H. Jorgensen, C. Sonne, J. Verreault, M. M. Vijayan, and G. W. Gabrielsen. 2010. "Exposure and effects assessment of persistent organohalogen contaminants in arctic wildlife and fish." Sci Total Environ 408 (15):2995-3043. 10.1016/j.scitotenv.2009.10.038.

Letcher, Robert J., Shaogang Chu, and Shirley-Anne Smyth. 2020. "Side-chain fluorinated polymer surfactants in biosolids from wastewater treatment plants." Journal of Hazardous Materials 388:122044. https://doi.org/10.1016/j.jhazmat.2020.122044.

Lewis, Asa J., Xiaoyan Yun, Daniel E. Spooner, Marie J. Kurz, Erica R. McKenzie, and Christopher M. Sales. 2022. "Exposure pathways and bioaccumulation of per- and polyfluoroalkyl substances in freshwater aquatic ecosystems: Key considerations." Science of The Total Environment 822:153561. https://doi.org/10.1016/j.scitotenv.2022.153561.

Li, Fei, Xinliang Fang, Zhenming Zhou, Xiaobin Liao, Jing Zou, Baoling Yuan, and Wenjie Sun. 2019. "Adsorption of perfluorinated acids onto soils: Kinetics, isotherms, and influences of soil properties." Science of The Total Environment 649:504-514. https://doi.org/10.1016/j.scitotenv.2018.08.209.

Li, Hongxia, David Ellis, and Don Mackay. 2007. "Measurement of Low Air−Water Partition Coefficients of Organic Acids by Evaporation from a Water Surface." Journal of Chemical & Engineering Data 52 (5):1580-1584. 10.1021/je600556d.

Li, H., S. Hammarstrand, B. Midberg, Y. Xu, Y. Li, D. S. Olsson, T. Fletcher, K. Jakobsson, and E. M. Andersson. 2022. "Cancer incidence in a Swedish cohort with high exposure to perfluoroalkyl substances in drinking water." Environ Res 204 (Pt C):112217. 10.1016/j.envres.2021.112217.

Li, Jianna, Conrad Austin, Stuart Moore, Brian R. Pinkard, and Igor V. Novosselov. 2023. "PFOS destruction in a continuous supercritical water oxidation reactor." Chemical Engineering Journal 451:139063. https://doi.org/10.1016/j.cej.2022.139063.

Li, Jianna, Brian R. Pinkard, Shuzhong Wang, and Igor V. Novosselov. 2022. "Review: Hydrothermal treatment of per- and polyfluoroalkyl substances (PFAS)." Chemosphere 307:135888. https://doi.org/10.1016/j.chemosphere.2022.135888.

Li, Mei-Hui. 2010. "Chronic Effects of Perfluorooctane Sulfonate and Ammonium Perfluorooctanoate on Biochemical Parameters, Survival and Reproduction of Daphnia magna." Journal of Health Science 56:104-111. 10.1248/jhs.56.104.

Li, M. H. 2009. "Toxicity of perfluorooctane sulfonate and perfluorooctanoic acid to plants and aquatic invertebrates." Environ Toxicol 24 (1):95-101. 10.1002/tox.20396.

Li, Na, Guang-Guo Ying, Huachang Hong, and Wen-Jing Deng. 2021. "Perfluoroalkyl substances in the urine and hair of preschool children, airborne particles in kindergartens, and drinking water in Hong Kong." Environmental Pollution 270:116219. https://doi.org/10.1016/j.envpol.2020.116219.

Li, Xiaona, Shuo Chen, Xie Quan, and Yaobin Zhang. 2011. "Enhanced Adsorption of PFOA and PFOS on Multiwalled Carbon Nanotubes under Electrochemical Assistance." Environmental Science & Technology 45 (19):8498-8505. 10.1021/es202026v.

Li, Xuchun, Jun Ma, Guifang Liu, Jingyun Fang, Siyang Yue, Yinghong Guan, Liwei Chen, and Xiaowei Liu. 2012. "Efficient Reductive Dechlorination of Monochloroacetic Acid by Sulfite/UV Process." Environmental Science & Technology 46 (13):7342-7349. 10.1021/es3008535.

Li, Xuemei, Leo Wai Yin Yeung, Muqi Xu, Sachi Taniyasu, Paul K. S. Lam, Nobuyoshi Yamashita, and Jiayin Dai. 2008. "Perfluorooctane sulfonate (PFOS) and other fluorochemicals in fish blood collected near the outfall of wastewater treatment plant (WWTP) in Beijing." Environmental Pollution 156 (3):1298-1303. https://doi.org/10.1016/j.envpol.2008.03.008.

Li, Y., A. Andersson, Y. Xu, D. Pineda, C. A. Nilsson, C. H. Lindh, K. Jakobsson, and T. Fletcher. 2022. "Determinants of serum half-lives for linear and branched perfluoroalkyl substances after long-term high exposure-A study in

Ronneby, Sweden.” Environ Int 163:107198. 10.1016/j.envint.2022.107198.

Li, Y., L. Barregard, Y. Xu, K. Scott, D. Pineda, C. H. Lindh, K. Jakobsson, and T. Fletcher. 2020. “Associations between perfluoroalkyl substances and serum lipids in a Swedish adult population with contaminated drinking water.” Environ Health 19 (1):33. 10.1186/s12940-020-00588-9.

Li, Y., L. Barregard, Y. Xu, K. Scott, D. Pineda, C. H. Lindh, K. Jakobsson, and T. Fletcher. 2020. “Associations between perfluoroalkyl substances and serum lipids in a Swedish adult population with contaminated drinking water.” Environ Health 19 (1):33. 10.1186/s12940-020-00588-9.

Li, Y., T. Fletcher, D. Mucs, K. Scott, C. H. Lindh, P. Tallving, and K. Jakobsson. 2018. “Half-lives of PFOS, PFHxS and PFOA after end of exposure to contaminated drinking water.” Occup Environ Med 75 (1):46-51. 10.1136/oemed-2017-104651.

Li, Yasong, Danielle P. Oliver, and Rai S. Kookana. 2018. “A critical analysis of published data to discern the role of soil and sediment properties in determining sorption of per and polyfluoroalkyl substances (PFASs).” Science of The Total Environment 628-629:110-120. https://doi.org/10.1016/j.scitotenv.2018.01.167.

Li, Y., D. H. Ramdhan, H. Naito, N. Yamagishi, Y. Ito, Y. Hayashi, Y. Yanagiba, A. Okamura, H. Tamada, F. J. Gonzalez, and T. Nakajima. 2011. “Ammonium perfluorooctanoate may cause testosterone reduction by adversely affecting testis in relation to PPARalpha.” Toxicol Lett 205 (3):265-72. 10.1016/j.toxlet.2011.06.015.

Li, Y., Y. Xu, T. Fletcher, K. Scott, C. Nielsen, D. Pineda, C. H. Lindh, D. S. Olsson, E. M. Andersson, and K. Jakobsson. 2021. “Associations between perfluoroalkyl substances and thyroid hormones after high exposure through drinking water.” Environ Res 194:110647. 10.1016/j.envres.2020.110647.

Liang, S. 2017. Enzymatic and electrochemical oxidation of emerging contaminants. Doctoral Dissertation. University of Georgia, Athens, GA.

Liang, S., R. D. Pierce Jr, H. Lin, S. Y. Chiang, and Q. J. Huang. 2018. “Electrochemical oxidation of PFOA and PFOS in concentrated waste streams.” Remediation Journal 28 (2):127-134. 10.1002/rem.21554.

Liang, Xiaoyan, Jianhua Cheng, Cao Yang, and Shewei Yang. 2016. “Factors influencing aqueous perfluorooctanoic acid (PFOA) photodecomposition by VUV irradiation in the presence of ferric ions.” Chemical Engineering Journal 298:291-299. https://doi.org/10.1016/j.cej.2016.03.150.

Liao, Zhaohui, and James Farrell. 2009. “Electrochemical oxidation of perfluorobutane sulfonate using boron-doped diamond film electrodes.” Journal of Applied Electrochemistry 39:1993-1999. https://doi.org/10.1007/s10800-009-9909-z.

Liberatore, Hannah K., Stephen R. Jackson, Mark J. Strynar, and James P. McCord. 2020. “Solvent Suitability for HFPO-DA (“GenX” Parent Acid) in Toxicological Studies.” Environmental Science & Technology Letters 7 (7):477-481. 10.1021/acs.estlett.0c00323.

Lieder, Paul H., Shu-Ching Chang, Raymond G. York, and John L. Butenhoff. 2009. “Toxicological evaluation of potassium perfluorobutanesulfonate in a 90-day oral gavage study with Sprague–Dawley rats.” Toxicology 255 (1):45-52. https://doi.org/10.1016/j.tox.2008.10.002.

Lieder, P. H., R. G. York, D. C. Hakes, S. C. Chang, and J. L. Butenhoff. 2009. “A two-generation oral gavage reproduction study with potassium perfluorobutanesulfonate (K+PFBS) in Sprague Dawley rats.” Toxicology 259 (1-2):33-45. 10.1016/j.tox.2009.01.027.

Lilienthal, H., H. H. Dieter, J. Holzer, and M. Wilhelm. 2017. “Recent experimental results of effects of perfluoroalkyl substances in laboratory animals – Relation to current regulations and guidance values.” Int J Hyg Environ Health 220 (4):766-775. 10.1016/j.ijheh.2017.03.001.

Lin, A. Y.-C., S. C. Panchangam, C.-Y. Chang, P. K. A. Hong, and H.-F. Hsueh. 2012. “Removal of perfluorooctanoic acid and perfluorooctane sulfonate via ozonation under alkaline condition.” Journal of Hazardous Materials 243:272-277. https://doi.org/10.1016/j.jhazmat.2012.10.029.

Lin, A. Y.-C., S. C. Panchangam, and C.-C. Lo. 2009. “The impact of semiconductor, electronics and optoelectronic industries on downstream perfluorinated chemical contamination in Taiwanese rivers.” Environmental Pollution 157 (4):1365-1372. https://doi.org/10.1016/j.envpol.2008.11.033.

Lin, A. Y.-C., S. C. Panchangam, Y.-T. Tsai, and T.-H. Yu. 2014. “Occurrence of perfluorinated compounds in the aquatic environment as found in science park effluent, river water, rainwater, sediments, and biotissues.” Environmental Monitoring and Assessment 186 (5):3265-3275. 10.1007/s10661-014-3617-9.

Lin, Chien-Yu, Lian-Yu Lin, Chih-Kang Chiang, Wei-Jie Wang, Yi-Ning Su, Kuan-Yu Hung, and Pau-Chung Chen. 2010. “Investigation of the Associations Between Low-Dose Serum Perfluorinated Chemicals and Liver Enzymes in US Adults.” Official journal of the American College of Gastroenterology | ACG 105 (6).

Lin, H., J. Niu, S. Ding, and L. Zhang. 2012. “Electrochemical degradation of perfluorooctanoic acid (PFOA) by Ti/SnO2–Sb, Ti/SnO2–Sb/PbO2 and Ti/SnO2–Sb/MnO2 anodes.” Water Research 46 (7):2281-2289. https://doi.org/10.1016/j.watres.2012.01.053.

Lin, Huiju, Sachi Taniyasu, Nobuyoshi Yamashita, Muhammad Kamran Khan, Saiyada Shadiah Masood, Sumayya Saied, and Haider Abbas Khwaja. 2022. “Per- and polyfluoroalkyl substances in the atmospheric total suspended particles in Karachi, Pakistan: Profiles, potential sources, and daily intake estimates.” Chemosphere 288:132432. https://doi.org/10.1016/j.chemosphere.2021.132432.

Lin, Huiju, Sachi Taniyasu, Eriko Yamazaki, Si Wei, Xinhong Wang, Nan Gai, Jin Hyo Kim, Heesoo Eun, Paul K. S. Lam, and Nobuyoshi Yamashita. 2020. “Per- and Polyfluoroalkyl Substances in the Air Particles of Asia: Levels, Seasonality, and Size-Dependent Distribution.” Environmental Science & Technology 54 (22):14182-14191. 10.1021/acs.est.0c03387.

Lin, H., Y. Wang, J. Niu, Z. Yue, and Q. Huang. 2015. “Efficient Sorption and Removal of Perfluoroalkyl Acids (PFAAs) from Aqueous Solution by Metal Hydroxides Generated in Situ by Electrocoagulation.” Environmental Science and Technology 49 (17):10562-10569. 10.1021/acs.est.5b02092.

Lin, J.-C., C.-Y. Hu, and S.-L. Lo. 2016. “Effect of surfactants on the degradation of perfluorooctanoic acid (PFOA) by ultrasonic (US) treatment.” Ultrasonics Sonochemistry 28:130-135. https://doi.org/10.1016/j.ultsonch.2015.07.007.

Lin, J.-C., S.-L. Lo, C.-Y. Hu, Y.-C. Lee, and J. Kuo. 2015. “Enhanced sonochemical degradation of perfluorooctanoic acid by sulfate ions.” Ultrasonics Sonochemistry 22:542-547. https://doi.org/10.1016/j.ultsonch.2014.06.006.

Lin, Yan, Staci L. Capozzi, Li Lin, and Lisa A. Rodenburg. 2021. “Source apportionment of perfluoroalkyl substances in Great Lakes fish.” Environmental Pollution 290:118047. https://doi.org/10.1016/j.envpol.2021.118047.

Lindell, Michael K., and Seong Nam Hwang. 2008. “Households’ Perceived Personal Risk and Responses in a Multihazard Environment.” Risk Analysis 28 (2):539-556. 10.1111/j.1539-6924.2008.01032.x.

Lindstrom, Andrew B., Mark J. Strynar, Amy D. Delinsky, Shoji F. Nakayama, Larry McMillan, E. Laurence Libelo, Michael Neill, and Lee Thomas. 2011. “Application of WWTP Biosolids and Resulting Perfluorinated Compound Contamination of Surface and Well Water in Decatur, Alabama, USA.” Environmental Science & Technology 45 (19):8015-8021. https://doi.org/10.1021/es1039425.

Lindstrom, Andrew B., Mark J. Strynar, and E. Laurence Libelo. 2011. “Polyfluorinated Compounds: Past, Present, and Future.” Environmental Science & Technology 45 (19):7954-7961. https://doi.org/10.1021/es2011622.

Lipp, P., F. Sacher, and G. Baldauf. 2010. “Removal of organic micro-pollutants during drinking water treatment by nanofiltration and reverse osmosis.” Desalination and Water Treatment 13 (1-3):226-237. https://doi.org/10.5004/dwt.2010.1063.

Lipson, D. S., B. Raine, and M. Webb. 2013. “Transport of Perfluorooctance Sulfonate (PFOS) in Fractured Bedrock at a Well-Characterized Site.” SETAC Europe Conference, Glasgow, Scotland.

Liss, P., and R. Duce. 1997. The Sea Surface and Global Change. Cambridge: Cambridge University Press. ISBN No. 9780521562737. DOI: 10.1017/CBO9780511525025.

Liu, Baolin, Hong Zhang, Dan Yao, Juying Li, Liuwei Xie, Xinxuan Wang, Yanping Wang, Guoqing Liu, and Bo Yang. 2015. “Perfluorinated compounds (PFCs) in the atmosphere of Shenzhen, China: Spatial distribution, sources and health risk assessment.” Chemosphere 138:511-518. https://doi.org/10.1016/j.chemosphere.2015.07.012.

Liu, Changhui, Victor W. C. Chang, and Karina Y. H. Gin. 2014. “Oxidative toxicity of perfluorinated chemicals in green mussel and bioaccumulation factor dependent quantitative structure–activity relationship.” Environmental Toxicology and Chemistry 33 (10):2323-2332. https://doi.org/10.1002/etc.2679.

Liu, Changhui, Victor W. C. Chang, Karina Y. H. Gin, and Viet Tung Nguyen. 2014. “Genotoxicity of perfluorinated chemicals (PFCs) to the green mussel (Perna viridis).” Science of The Total Environment 487:117-122. https://doi.org/10.1016/j.scitotenv.2014.04.017.

Liu, Changhui, and Karina Yew-Hoong Gin. 2018. “Immunotoxicity in green mussels under perfluoroalkyl substance (PFAS) exposure: Reversible response and response model development.” Environmental Toxicology and Chemistry 37 (4):1138-1145. https://doi.org/10.1002/etc.4060.

Liu, Changhui, Karina Y. H. Gin, and Victor W. C. Chang. 2014. “Multi-biomarker responses in green mussels exposed to PFCs: effects at molecular, cellular, and physiological levels.” Environmental Science and Pollution Research 21 (4):2785-2794. 10.1007/s11356-013-2216-6.

Liu, Chen, and Jinxia Liu. 2016. “Aerobic biotransformation of polyfluoroalkyl phosphate esters (PAPs) in soil.” Environmental Pollution 212:230-237. https://doi.org/10.1016/j.envpol.2016.01.069.

Liu, Charlie J., David Werner, and Christopher Bellona. 2019. “Removal of per- and polyfluoroalkyl substances (PFASs) from contaminated groundwater using granular activated carbon: a pilot-scale study with breakthrough modeling.” Environmental Science: Water Research & Technology 5 (11):1844-1853. 10.1039/C9EW00349E.

Liu, C. S., C. P. Higgins, F. Wang, and K. Shih. 2012. “Effect of temperature on oxidative transformation of perfluorooctanoic acid (PFOA) by persulfate activation in water.” Separation and Purification Technology 91:46-51. https://doi.org/10.1016/j.seppur.2011.09.047.

Liu, J. 2020. High-Performance Treatment of PFASs from Investigation-derived Waste: Integrating Advanced Oxidation-Reduction and Membrane Concentration. SERDP Project ER 18-1497. Alexandria VA: Strategic Environmental Research and Development Program. https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/ER18-1497.

Liu, Jinxia, and Linda S. Lee. 2005. “Solubility and Sorption by Soils of 8:2 Fluorotelomer Alcohol in Water and Cosolvent Systems.” Environmental Science & Technology 39 (19):7535-7540. 10.1021/es051125c.

Liu, J., and L. S. Lee. 2007. “Effect of Fluorotelomer Alcohol Chain Length on Aqueous Solubility and Sorption by Soils.” Environmental Science & Technology 41 (15):5357-5362. 10.1021/es070228n.

Liu, Jinxia, Linda S. Lee, Loring F. Nies, Cindy H. Nakatsu, and Ronald F. Turco. 2007. “Biotransformation of 8:2 Fluorotelomer Alcohol in Soil and by Soil Bacteria Isolates.” Environmental Science & Technology 41 (23):8024-8030. 10.1021/es0708722.

Liu, J., J. Li, Y. Zhao, Y. Wang, L. Zhang, and Y. Wu. 2010. “The occurrence of perfluorinated alkyl compounds in human milk from different regions of China.” Environ Int 36 (5):433-8. 10.1016/j.envint.2010.03.004.

Liu, Jinxia, and Sandra Mejia Avendaño. 2013. “Microbial degradation of polyfluoroalkyl chemicals in the environment: A review.” Environment International 61:98-114. https://doi.org/10.1016/j.envint.2013.08.022.

Liu, Jiaoqin, Ruijuan Qu, Zunyao Wang, Itza Mendoza-Sanchez, and Virender K. Sharma. 2017. “Thermal- and photo-induced degradation of perfluorinated carboxylic acids: Kinetics and mechanism.” Water Research 126:12-18. https://doi.org/10.1016/j.watres.2017.09.003.

Liu, Jinxia, Ning Wang, Robert C. Buck, Barry W. Wolstenholme, Patrick W. Folsom, Lisa M. Sulecki, and Cheryl A. Bellin. 2010. “Aerobic biodegradation of [14C] 6:2 fluorotelomer alcohol in a flow-through soil incubation system.” Chemosphere 80 (7):716-723. https://doi.org/10.1016/j.chemosphere.2010.05.027.

Liu, Jinxia, Ning Wang, Bogdan Szostek, Robert C. Buck, Patricia K. Panciroli, Patrick W. Folsom, Lisa M. Sulecki, and Cheryl A. Bellin. 2010. “6-2 Fluorotelomer alcohol aerobic biodegradation in soil and mixed bacterial culture.” Chemosphere 78 (4):437-444. https://doi.org/10.1016/j.chemosphere.2009.10.044.

Liu, Jinxia, Guowei Zhong, Wei Li, and Sandra Mejia Avendaño. 2019. “Isomer-specific biotransformation of perfluoroalkyl sulfonamide compounds in aerobic soil.” Science of The Total Environment 651:766-774. https://doi.org/10.1016/j.scitotenv.2018.09.214.

Liu, Min, Gabriel Munoz, Sung Vo Duy, Sébastien Sauvé, and Jinxia Liu. 2022. “Per- and Polyfluoroalkyl Substances in Contaminated Soil and Groundwater at Airports: A Canadian Case Study.” Environmental Science & Technology 56 (2):885-895. 10.1021/acs.est.1c04798.

Liu, Shanshan, Shiyi Zhao, Zhihong Liang, Fei Wang, Feiyun Sun, and Da Chen. 2021. “Perfluoroalkyl substances (PFASs) in leachate, fly ash, and bottom ash from waste incineration plants: Implications for the environmental release of PFAS.” Science of The Total Environment 795:148468. https://doi.org/10.1016/j.scitotenv.2021.148468.

Liu, Wanyang, Shengying Chen, Kouji H. Harada, and Akio Koizumi. 2011. “Analysis of perfluoroalkyl carboxylates in vacuum cleaner dust samples in Japan.” Chemosphere 85 (11):1734-1741. https://doi.org/10.1016/j.chemosphere.2011.09.024.

Liu, W., Y. Jin, X. Quan, K. Sasaki, N. Saito, S. F. Nakayama, I. Sato, and S. Tsuda. 2009. “Perfluorosulfonates and perfluorocarboxylates in snow and rain in Dalian, China.” Environ Int 35 (4):737-42. 10.1016/j.envint.2009.01.016.

Liu, W., B. Yang, L. Wu, W. Zou, X. Pan, T. Zou, F. Liu, L. Xia, X. Wang, and D. Zhang. 2015. “Involvement of NRF2 in Perfluorooctanoic Acid-Induced Testicular Damage in Male Mice.” Biol Reprod 93 (2):41. 10.1095/biolreprod.115.128819.

Liu, Xiaotu, Da Chen, Bin Wang, Fangping Xu, Yiming Pang, Le Zhang, Yali Zhang, Lei Jin, Zhiwen Li, and Aiguo Ren. 2020. “Does Low Maternal Exposure to Per- and Polyfluoroalkyl Substances Elevate the Risk of Spontaneous Preterm Birth? A Nested Case–Control Study in China.” Environmental Science & Technology 54 (13):8259-8268. 10.1021/acs.est.0c01930.

Liu, Xiaoyu, Zhishi Guo, Edgar E. Folk, and Nancy Roache. 2014. “Determination of fluorotelomer alcohols in selected consumer products and preliminary investigation of their fate in the indoor environment.” Chemosphere 129:81-86. https://doi.org/10.1016/j.chemosphere.2014.06.012.

Liu, Xiaoyu, Zhishi Guo, Kenneth A. Krebs, Robert H. Pope, and Nancy F. Roache. 2014. “Concentrations and trends of perfluorinated chemicals in potential indoor sources from 2007 through 2011 in the US.” Chemosphere 98:51-57. https://doi.org/10.1016/j.chemosphere.2013.10.001.

Liu, Yanna, Lisa A. D’Agostino, Guangbo Qu, Guibin Jiang, and Jonathan W. Martin. 2019. “High-resolution mass spectrometry (HRMS) methods for nontarget discovery and characterization of poly- and per-fluoroalkyl substances (PFASs) in environmental and human samples.” TrAC Trends in Analytical Chemistry 121:115420. https://doi.org/10.1016/j.trac.2019.02.021.

Liu, Zhaoyang, Yonglong Lu, Xin Song, Kevin Jones, Andrew J. Sweetman, Andrew C. Johnson, Meng Zhang, Xiaotian Lu, and Chao Su. 2019. “Multiple crop bioaccumulation and human exposure of perfluoroalkyl substances around a mega fluorochemical industrial park, China: Implication for planting optimization and food safety.” Environment International 127:671-684. https://doi.org/10.1016/j.envint.2019.04.008.

Liu, Zhaoyang, Yonglong Lu, Tieyu Wang, Pei Wang, Qifeng Li, Andrew C. Johnson, Suriyanarayanan Sarvajayakesavalu, and Andrew J. Sweetman. 2016. “Risk assessment and source identification of perfluoroalkyl acids in surface and ground water: Spatial distribution around a mega-fluorochemical industrial park, China.” Environment International 91:69-77. https://doi.org/10.1016/j.envint.2016.02.020.

Llorca, Marta, Gabriella Schirinzi, Mònica Martínez, Damia Barcelo, and Marinella Farré. 2018. “Adsorption of perfluoroalkyl substances on microplastics under environmental conditions.” Environmental Pollution 235:680-691. https://doi.org/10.1016/j.envpol.2017.12.075.

Locke, Bruce R., Petr Lukes, and Jean-Louis Brisset. 2012. “Elementary Chemical and Physical Phenomena in Electrical

Discharge Plasma in Gas–Liquid Environments and in Liquids." Plasma Chemistry and Catalysis in Gases and Liquids:185-241. https://doi.org/10.1002/9783527649525.ch6.

Loewen, M., F. Wania, F. Wang, and G. Tomy. 2008. "Altitudinal transect of atmospheric and aqueous fluorinated organic compounds in Western Canada." Environmental Science & Technology 42 (7):2374-9. https://doi.org/10.1021/es702276c.

Löfstedt Gilljam, John, Juliana Leonel, Ian T. Cousins, and Jonathan P. Benskin. 2016. "Is Ongoing Sulfluramid Use in South America a Significant Source of Perfluorooctanesulfonate (PFOS)? Production Inventories, Environmental Fate, and Local Occurrence." Environmental Science & Technology 50 (2):653-659. 10.1021/acs.est.5b04544.

Lohmann, Rainer, Ian T. Cousins, Jamie C. DeWitt, Juliane Glüge, Gretta Goldenman, Dorte Herzke, Andrew B. Lindstrom, Mark F. Miller, Carla A. Ng, Sharyle Patton, Martin Scheringer, Xenia Trier, and Zhanyun Wang. 2020. "Are Fluoropolymers Really of Low Concern for Human and Environmental Health and Separate from Other PFAS?" Environmental Science & Technology 54 (20):12820-12828. 10.1021/acs.est.0c03244.

Lohmann, Rainer, Elena Jurado, Henk A. Dijkstra, and Jordi Dachs. 2013. "Vertical eddy diffusion as a key mechanism for removing perfluorooctanoic acid (PFOA) from the global surface oceans." Environmental Pollution 179:88-94. https://doi.org/10.1016/j.envpol.2013.04.006.

Loi, Eva I. H., Leo W. Y. Yeung, Scott A. Mabury, and Paul K. S. Lam. 2013. "Detections of Commercial Fluorosurfactants in Hong Kong Marine Environment and Human Blood: A Pilot Study." Environmental Science & Technology 47 (9):4677-4685. 10.1021/es303805k.

Loi-Brügger, A., Stefan Panglisch, Grit Hoffmann, P. Buchta, R. Gimbel, and C. J. Nacke. 2008. "Removal of trace organic substances from river bank filtrate – Performance study of RO and NF membranes." Water Supply 8 (1):85-92. https://doi.org/10.2166/ws.2008.021.

Long, Y., Y. Wang, G. Ji, L. Yan, F. Hu, and A. Gu. 2013. "Neurotoxicity of perfluorooctane sulfonate to hippocampal cells in adult mice." PLoS One 8 (1):e54176. 10.1371/journal.pone.0054176.

Loos, Robert, Giovanni Locoro, Sara Comero, Serafino Contini, David Schwesig, Friedrich Werres, Peter Balsaa, Oliver Gans, Stefan Weiss, Ludek Blaha, Monica Bolchi, and Bernd Gawlik. 2010. "Pan-European Survey on the Occurrence of Selected Polar Organic Persistent Pollutants in Ground Water." Water Research 44 (14):4115-4126. https://doi.org/10.1016/j.watres.2010.05.032.

López-Fontán, José L., Félix Sarmiento, and Pablo C. Schulz. 2005. "The aggregation of sodium perfluorooctanoate in water." Colloid and Polymer Science 283 (8):862-871. 10.1007/s00396-004-1228-7.

Lorber, M., G. E. Eaglesham, P. Hobson, L. M. L. Toms, J. F. Mueller, and J. S. Thompson. 2015. "The effect of ongoing blood loss on human serum concentrations of perfluorinated acids." Chemosphere 118:170-177. https://doi.org/10.1016/j.chemosphere.2014.07.093.

Lorber, M., and P. P. Egeghy. 2011. "Simple intake and pharmacokinetic modeling to characterize exposure of Americans to perfluoroctanoic acid, PFOA." Environ Sci Technol 45 (19):8006-14. 10.1021/es103718h.

Loria, K. 2022. "Dangerous PFAS Chemicals Are in Your Food Packaging." Consumer Reports, Last Modified March 24, 2022. accessed 2022. https://www.consumerreports.org/health/food-contaminants/dangerous-pfas-chemicals-are-in-your-food-packaging-a3786252074/.

Loveless, S. E., C. Finlay, N. E. Everds, S. R. Frame, P. J. Gillies, J. C. O'Connor, C. R. Powley, and G. L. Kennedy. 2006. "Comparative responses of rats and mice exposed to linear/branched, linear, or branched ammonium perfluorooctanoate (APFO)." Toxicology 220 (2-3):203-17. 10.1016/j.tox.2006.01.003.

Loveless, S. E., D. Hoban, G. Sykes, S. R. Frame, and N. E. Everds. 2008. "Evaluation of the immune system in rats and mice administered linear ammonium perfluorooctanoate." Toxicol Sci 105 (1):86-96. 10.1093/toxsci/kfn113.

Loveless, S. E., B. Slezak, T. Serex, J. Lewis, P. Mukerji, J. C. O'Connor, E. M. Donner, S. R. Frame, S. H. Korzeniowski, and R. C. Buck. 2009. "Toxicological evaluation of sodium perfluorohexanoate." Toxicology 264 (1-2):32-44.

10.1016/j.tox.2009.07.011.

Lu, Dingnan, Sha Sha, Jiayue Luo, Zhuangrong Huang, and Xiaoqi Zhang Jackie. 2020. “Treatment train approaches for the remediation of per- and polyfluoroalkyl substances (PFAS): A critical review.” Journal of Hazardous Materials 386:121963. https://doi.org/10.1016/j.jhazmat.2019.121963.

Lu, Dingnan, Sha Sha, Jiayue Luo, Zhuangrong Huang, and Xiaoqi Zhang Jackie. 2020. “Treatment train approaches for the remediation of per- and polyfluoroalkyl substances (PFAS): A critical review.” Journal of Hazardous Materials 386:121963. https://doi.org/10.1016/j.jhazmat.2019.121963.

Lu, Guo-Hui, Xing-Chun Jiao, Hai-Tao Piao, Xiao-Chun Wang, Shu Chen, Ke-Yan Tan, Nan Gai, Xiao-Cai Yin, Yong-Liang Yang, and Jing Pan. 2018. “The Extent of the Impact of a Fluorochemical Industrial Park in Eastern China on Adjacent Rural Areas.” Archives of Environmental Contamination and Toxicology 74 (3):484-491. 10.1007/s00244-017-0458-x.

Lu, Guang-hua, Jian-chao Liu, Li-sha Sun, and Lu-jin Yuan. 2015. “Toxicity of perfluorononanoic acid and perfluorooctane sulfonate to Daphnia magna.” Water Science and Engineering 8 (1):40-48. https://doi.org/10.1016/j.wse.2015.01.001.

Lu, Hao, Zhen-min Ma, Xiao Zhang, Peng Jiang, Ming Wen, and Wei-wei Yu. 2017. “Source Apportionment of Perfluorinated Compounds (PFCs) in Shallow Groundwater Around A Fluorine Chemistry Industrial Park in North China.” DEStech Transactions on Environment, Energy and Earth Sciences:207-212. https://doi.org/10.12783/dteees/ese2017/14349.

Lu, S., and S.M. Bartell. 2020. “Serum PFAS Calculator for Adults. Version 1.2.” https://www.ics.uci.edu/~sbartell/pfascalc.html.

Lu, Y., B. Luo, J. Li, and J. Dai. 2016. “Perfluorooctanoic acid disrupts the blood-testis barrier and activates the TNFalpha/p38 MAPK signaling pathway in vivo and in vitro.” Arch Toxicol 90 (4):971-83. 10.1007/s00204-015-1492-y.

Lucas, R.M., and A.J. McMichael. 2005. “Association or causation: evaluating links between “environment and disease”.” Bulletin of the World Health Organization 83 (10):792-795. https://www.who.int/publications/journals/bulletin.

Luebker, D. J., M. T. Case, R. G. York, J. A. Moore, K. J. Hansen, and J. L. Butenhoff. 2005. “Two-generation reproduction and cross-foster studies of perfluorooctanesulfonate (PFOS) in rats.” Toxicology 215 (1-2):126-48. 10.1016/j.tox.2005.07.018.

Luebker, D. J., R. G. York, K. J. Hansen, J. A. Moore, and J. L. Butenhoff. 2005. “Neonatal mortality from in utero exposure to perfluorooctanesulfonate (PFOS) in Sprague-Dawley rats: dose-response, and biochemical and pharamacokinetic parameters.” Toxicology 215 (1-2):149-69. 10.1016/j.tox.2005.07.019.

Lukes, P., A.T. Appleton, and B. R. Locke. 2004. “Hydrogen peroxide and ozone formation in hybrid gas-liquid electrical discharge Reactors.” IEEE Transactions on Industry Applications 40 (1):60-67. 10.1109/TIA.2003.821799.

Lukes, P., M. Clupek, V. Babicky, and P. Sunka. 2005. “Plasma-Surface Interactions Induced by Pulsed Corona Discharge in Water.” 2005 IEEE International Conference on Plasma Science, Monterey, CA, 20-23 June 2005 https://doi.org/10.1109/PLASMA.2005.359497.

Lundgren, R.E., and A.H. McMakin. 2013. Risk Communication: A Handbook for Communicating Environmental, Safety, and Health Risks, Fifth Edition. Hoboken, NJ: John Wiley & Sons, Inc. ISBN No. 978-1118456934.

Lundgren, R.E., and A.H. McMakin. 2018. Risk Communication: A Handbook for Communicating Environmental, Safety, and Health Risks, 6th Edition. Hoboken, NJ: IEEE Press, John Wiley & Sons, Inc. ISBN No. 978-1-119-45615-5.

Lundin, J. I., B. H. Alexander, G. W. Olsen, and T. R. Church. 2009. “Ammonium perfluorooctanoate production and occupational mortality.” Epidemiology 20 (6):921-8. 10.1097/EDE.0b013e3181b5f395.

Luo, Q. 2015. Degradation of Perfluoroalkyl Acids by Enzyme Catalyzed Oxidative Humification Reactions. University of Georgia, Athens Georgia.

Luo, Qi, Junhe Lu, Hao Zhang, Zunyao Wang, Mingbao Feng, Sheau-Yun Dora Chiang, David Woodward, and Qingguo Huang. 2015. “Laccase-Catalyzed Degradation of Perfluorooctanoic Acid.” Environmental Science & Technology

Letters 2 (7):198-203. 10.1021/acs.estlett.5b00119.

Lupton, Sara J., Janice K. Huwe, David J. Smith, Kerry L. Dearfield, and John J. Johnston. 2014. “Distribution and Excretion of Perfluorooctane Sulfonate (PFOS) in Beef Cattle (Bos taurus).” Journal of Agricultural and Food Chemistry 62 (5):1167-1173. 10.1021/jf404355b.

Lustgarten, A. 2018. “Bombs in our Backyard: How the EPA and the Pentagon Downplayed a Growing Toxic Threat.” ProPublica, Last Modified July 9, 2018. accessed 2021. https://www.propublica.org/article/how-the-epa-and-the-pentagon-downplayed-toxic-pfas-chemicals.

Luz, A. L., J. K. Anderson, P. Goodrum, and J. Durda. 2019. “Perfluorohexanoic acid toxicity, part I: development of a chronic human health toxicity value for use in risk assessment.” Regulatory Toxicology and Pharmacology 103:41-55.

Lv, Z., G. Li, Y. Li, C. Ying, J. Chen, T. Chen, J. Wei, Y. Lin, Y. Jiang, Y. Wang, B. Shu, B. Xu, and S. Xu. 2013. “Glucose and lipid homeostasis in adult rat is impaired by early-life exposure to perfluorooctane sulfonate.” Environ Toxicol 28 (9):532-42. 10.1002/tox.20747.

Lyu, Xian-Jin, Wen-Wei Li, Paul K. S. Lam, and Han-Qing Yu. 2015. “Boiling significantly promotes photodegradation of perfluorooctane sulfonate.” Chemosphere 138:324-327. https://doi.org/10.1016/j.chemosphere.2015.06.027.

Lyu, Xian-Jin, Wen-Wei Li, Paul K. S. Lam, and Han-Qing Yu. 2015. “Insights into perfluorooctane sulfonate photodegradation in a catalyst-free aqueous solution.” Scientific Reports 5:9353. https://doi.org/10.1038/srep09353.

Lyu, Xian-Jin, Yong Liu, Chen Chen, Matthew Sima, Jian-Fang Lyu, Zhi-Yuan Ma, and Shan Huang. 2020. “Enhanced use of foam fractionation in the photodegradation of perfluorooctane sulfonate (PFOS).” Separation and Purification Technology 253:117488. https://doi.org/10.1016/j.seppur.2020.117488.

Lyu, Ying, and Mark L. Brusseau. 2020. “The influence of solution chemistry on air-water interfacial adsorption and transport of PFOA in unsaturated porous media.” Science of The Total Environment 713:136744. https://doi.org/10.1016/j.scitotenv.2020.136744.

MA DEP. 2018. “Commonwealth Begins Program to Remove Legacy Firefighting Foams from Fire Department Stockpiles.” Massachusetts Department of Environmental Protection. https://www.mass.gov/news/commonwealth-begins-program-to-remove-legacy-firefighting-foams-from-fire-department

MA DEP. 2019. Technical Support Document – Per- and Polyfluoroalkyl Substances (PFAS): An Updated Subgroup Approach to Groundwater and Drinking Water Values. Boston, MA: Department of Environmental Protection. https://www.mass.gov/doc/per-and-polyfluoroalkyl-substances-pfas-an-updated-subgroup-approach-to-groundwater-and/download

MA DEP. 2020. Interim Guidance on Sampling and Analysis for PFAS at Disposal Sites Regulated under the Massachusetts Contingency Plan.

Ma, Jing, Hongkai Zhu, and Kurunthachalam Kannan. 2020. “Fecal Excretion of Perfluoroalkyl and Polyfluoroalkyl Substances in Pets from New York State, United States.” Environmental Science & Technology Letters 7 (3):135-142. 10.1021/acs.estlett.9b00786.

Ma, Si-Han, Ming-Hong Wu, Liang Tang, Rui Sun, Chao Zang, Jia-Jia Xiang, Xue-Xia Yang, Xu Li, and Gang Xu. 2017. “EB degradation of perfluorooctanoic acid and perfluorooctane sulfonate in aqueous solution.” Nuclear Science and Techniques 28 (9):137. 10.1007/s41365-017-0278-8.

MacDonald, M. M., A. L. Warne, N. L. Stock, S. A. Mabury, K. R. Solomon, and P. K. Sibley. 2004. “Toxicity of perfluorooctane sulfonic acid and perfluorooctanoic acid to Chironomus tentans.” Environ Toxicol Chem 23 (9):2116-23. 10.1897/03-449.

MacInnis, John J., Igor Lehnherr, Derek C. G. Muir, Kyra A. St. Pierre, Vincent L. St. Louis, Christine Spencer, and Amila O. De Silva. 2019. “Fate and Transport of Perfluoroalkyl Substances from Snowpacks into a Lake in the High Arctic of Canada.” Environmental Science & Technology 53 (18):10753-10762. 10.1021/acs.est.9b03372.

Macon, M. B., L. R. Villanueva, K. Tatum-Gibbs, R. D. Zehr, M. J. Strynar, J. P. Stanko, S. S. White, L. Helfant, and S. E. Fenton. 2011. “Prenatal perfluorooctanoic acid exposure in CD-1 mice: low-dose developmental effects and internal dosimetry.” Toxicol Sci 122 (1):134-45. 10.1093/toxsci/kfr076.

Mahinroosta, Reza, and Lalantha Senevirathna. 2020. “A review of the emerging treatment technologies for PFAS contaminated soils.” Journal of Environmental Management 255:109896. https://doi.org/10.1016/j.jenvman.2019.109896.

Maine CDC. 2014. Human health risk-based screening levels for perfluoroalkyl compounds. Maine Center for Disease Control and Prevention. Department of Health and Human Services.

Maine State Legislature. 2020. An Act to Prohibit the Contamination of Clean Soils with So-called Forever Chemicals. LD 1911. https://legislature.maine.gov/LawMakerWeb/summary.asp?ID=280082389.

Maine State Legislature. 2021. An Act to Stop Perfluoroalkyl and Polyfluoroalkyl Substances Pollution. 130LR0942(05). http://www.mainelegislature.org/legis/bills/getPDF.asp?paper=HP1113&item=5&snum=130.

Mamsen, Linn Salto, Bo A. G. Jönsson, Christian H. Lindh, Rasmus H. Olesen, Agnete Larsen, Erik Ernst, Thomas W. Kelsey, and Claus Yding Andersen. 2017. “Concentration of perfluorinated compounds and cotinine in human foetal organs, placenta, and maternal plasma.” Science of The Total Environment 596 (Supplement C):97-105. https://doi.org/10.1016/j.scitotenv.2017.04.058.

Marine, F. 2020. “Class I UIC wells to manage PFAS in wastewaters.” 2020 UIC Conference, San Antonio, TX, February 17, 2020 https://texasmolecular.com/wp-content/uploads/2020/02/Class-1-UIC-Wells-for-PFAS-Wastewater.pdf.

MAROS. 2012. User’s Guide and Technical Manual Software Version 3.0. Houston, TX: GSI Environmental.

Marques, E. S., J. Agudelo, E. M. Kaye, S. M. S. Modaresi, M. Pfohl, J. Bečanová, W. Wei, M. Polunas, M. Goedken, and A. L. Slitt. 2021. “The role of maternal high fat diet on mouse pup metabolic endpoints following perinatal PFAS and PFAS mixture exposure.” Toxicology 462:152921. 10.1016/j.tox.2021.152921.

Marquez, N., R. Steward, C. Lawrence, and J. Kirk. 2016. “A Novel Adsorption Product for the Treatment of Per-and Poly-Fluorinated Alkyl Substances (PFAS) in Wastewater from Airport Fire-training Grounds.” Battelle Conference, Palm Springs, CA.

Martin, Déborah, Gabriel Munoz, Sandra Mejia-Avendaño, Sung Vo Duy, Yuan Yao, Konstantin Volchek, Carl E. Brown, Jinxia Liu, and Sébastien Sauvé. 2019. “Zwitterionic, cationic, and anionic perfluoroalkyl and polyfluoroalkyl substances integrated into total oxidizable precursor assay of contaminated groundwater.” Talanta 195:533-542. https://doi.org/10.1016/j.talanta.2018.11.093.

Martin, Jonathan W., Brian J. Asher, Sanjay Beesoon, Jonathan P. Benskin, and Matthew S. Ross. 2010. “PFOS or PreFOS? Are perfluorooctane sulfonate precursors (PreFOS) important determinants of human and environmental perfluorooctane sulfonate (PFOS) exposure?” Journal of Environmental Monitoring 12 (11):1979-2004. 10.1039/C0EM00295J.

Martin, Jonathan W., Katie Chan, Scott A. Mabury, and Peter J. O’Brien. 2009. “Bioactivation of fluorotelomer alcohols in isolated rat hepatocytes.” Chemico-Biological Interactions 177 (3):196-203. https://doi.org/10.1016/j.cbi.2008.11.001.

Martin, J. W., D. A. Ellis, S. A. Mabury, M. D. Hurley, and T. J. Wallington. 2006. “Atmospheric Chemistry of Perfluoroalkanesulfonamides: Kinetic and Product Studies of the OH Radical and Cl Atom Initiated Oxidation of N-Ethyl Perfluorobutanesulfonamide.” Environmental Science & Technology 40 (3):864-872. 10.1021/es051362f.

Martin, Jonathan W., Scott A. Mabury, and Peter J. O’Brien. 2005. “Metabolic products and pathways of fluorotelomer alcohols in isolated rat hepatocytes.” Chemico-Biological Interactions 155 (3):165-180. https://doi.org/10.1016/j.cbi.2005.06.007.

Martin, J. W., S. A. Mabury, K. R. Solomon, and D. C. Muir. 2003. “Bioconcentration and tissue distribution of perfluorinated acids in rainbow trout (Oncorhynchus mykiss).” Environ Toxicol Chem 22 (1):196-204.

Martin, J. W., S. A. Mabury, K. R. Solomon, and D. C. Muir. 2003. “Dietary accumulation of perfluorinated acids in juvenile rainbow trout (Oncorhynchus mykiss).” Environ Toxicol Chem 22 (1):189-95.

Martin, J. W., S. A. Mabury, K. R. Solomon, and D. C. Muir. 2013. “Progress toward understanding the bioaccumulation of perfluorinated alkyl acids.” Environ Toxicol Chem 32 (11):2421-3. 10.1002/etc.2376.

Martin, Jonathan W., Derek C. G. Muir, Cheryl A. Moody, David A. Ellis, Wai Chi Kwan, Keith R. Solomon, and Scott A. Mabury. 2002. “Collection of Airborne Fluorinated Organics and Analysis by Gas Chromatography/Chemical Ionization Mass Spectrometry.” Analytical Chemistry 74 (3):584-590. 10.1021/ac015630d.

Martin, Jonathan W., Marla M. Smithwick, Birgit M. Braune, Paul F. Hoekstra, Derek C. G. Muir, and Scott A. Mabury. 2004. “Identification of Long-Chain Perfluorinated Acids in Biota from the Canadian Arctic.” Environmental Science & Technology 38 (2):373-380. 10.1021/es034727+.

Martin, Jonathan W., D. Michael Whittle, Derek C. G. Muir, and Scott A. Mabury. 2004. “Perfluoroalkyl Contaminants in a Food Web from Lake Ontario.” Environmental Science & Technology 38 (20):5379-5385. 10.1021/es049331s.

Martin, M. T., R. J. Brennan, W. Hu, E. Ayanoglu, C. Lau, H. Ren, C. R. Wood, J. C. Corton, R. J. Kavlock, and D. J. Dix. 2007. “Toxicogenomic study of triazole fungicides and perfluoroalkyl acids in rat livers predicts toxicity and categorizes chemicals based on mechanisms of toxicity.” Toxicol Sci 97 (2):595-613. 10.1093/toxsci/kfm065.

Marziali, Laura, Federica Rosignoli, Sara Valsecchi, Stefano Polesello, and Fabrizio Stefani. 2019. “Effects of Perfluoralkyl Substances on a Multigenerational Scale: A Case Study with Chironomus riparius (Diptera, Chironomidae).” Environmental Toxicology and Chemistry 38 (5):988-999. 10.1002/etc.4392.

Masoner, Jason R., Dana W. Kolpin, Isabelle M. Cozzarelli, Kelly L. Smalling, Stephanie C. Bolyard, Jennifer A. Field, Edward T. Furlong, James L. Gray, Duncan Lozinski, Debra Reinhart, Alix Rodowa, and Paul M. Bradley. 2020. “Landfill leachate contributes per-/poly-fluoroalkyl substances (PFAS) and pharmaceuticals to municipal wastewater.” Environmental Science: Water Research & Technology 6 (5):1300-1311. 10.1039/D0EW00045K.

Massey, R., and L. Pollard. 2023. “Playing on Plastic: Artificial Turf Hazards and Safer Alternatives.” Collaborative for Health and Environment, Last Modified 8/21/23. https://www.healthandenvironment.org/join-us/blog/playing-on-plastic-artificial-turf-hazards-and-safer-alternatives.

Matrix Scientific. “Matrix Scientific web page.” http://www.matrixscientific.com.

Maul, Gabriel A., Youngwoon Kim, Adib Amini, Qiong Zhang, and Treavor H. Boyer. 2014. “Efficiency and life cycle environmental impacts of ion-exchange regeneration using sodium, potassium, chloride, and bicarbonate salts.” Chemical Engineering Journal 254:198-209. https://doi.org/10.1016/j.cej.2014.05.086.

Mayilswami, S., K. Krishnan, M. Megharaj, and R. Naidu. 2014. Effect of perfluorooctane sulfonate (PFOS) on survival and DNA damage of earthworm in OECD soil compared to natural soils. Australia: Centre for Environmental Risk Assessment and Remediation (CERAR) and Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE).

Mazzoni, M., S. Polesello, M. Rusconi, and S. Valsecchi. 2015. “Investigating the occurrence of C8-based perfluorinated substitutes in Italian waters.” Normal Bulletin 4:5-7.

McCarthy, Chris, William Kappleman, and William DiGuiseppi. 2017. “Ecological Considerations of Per- and Polyfluoroalkyl Substances (PFAS).” Current Pollution Reports 3 (4):289-301. https://doi.org/10.1007/s40726-017-0070-8.

McCarthy, Christopher, Shaun Roark, and Elizabeth T. Middleton. 2021. “Considerations for Toxicity Experiments and Risk Assessments with PFAS Mixtures.” Integrated Environmental Assessment and Management 17 (4):697-704. https://doi.org/10.1002/ieam.4415.

McCarthy, Christopher J., Shaun A. Roark, Demitria Wright, Kelly O’Neal, Brett Muckey, Mike Stanaway, Justin Rewerts, Jennifer Field, Todd Anderson, and Christopher J. Salice. 2021. “Toxicological Response of Chironomus dilutus in Single Chemical and Binary Mixture Exposure Experiments with Six Perfluoralkyl Substances.” Environmental Toxicology and Chemistry 40 (8):2319-2333. https://doi.org/10.1002/etc.5066.

McCleaf, Philip, Sophie Englund, Anna Östlund, Klara Lindegren, Karin Wiberg, and Lutz Ahrens. 2017. “Removal efficiency of multiple poly- and perfluoroalkyl substances (PFASs) in drinking water using granular activated carbon (GAC) and anion exchange (AE) column tests.” Water Research 120:77-87. https://doi.org/10.1016/j.watres.2017.04.057.

McCleaf, Philip, Ylva Kjellgren, and Lutz Ahrens. 2021. “Foam fractionation removal of multiple per- and polyfluoroalkyl substances from landfill leachate.” AWWA Water Science 3 (5):e1238. https://doi.org/10.1002/aws2.1238.

McCleaf, Philip, Ylva Kjellgren, and Lutz Ahrens. 2021. “Foam fractionation removal of multiple per- and polyfluoroalkyl substances from landfill leachate.” AWWA Water Science 3 (5):e1238. https://doi.org/10.1002/aws2.1238.

McCord, James, and Mark Strynar. 2019. “Identification of Per- and Polyfluoroalkyl Substances in the Cape Fear River by High Resolution Mass Spectrometry and Nontargeted Screening.” Environmental Science & Technology. 10.1021/acs.est.8b06017.

McCord, James P., Mark J. Strynar, John W. Washington, Erica L. Bergman, and Sandra M. Goodrow. 2020. “Emerging Chlorinated Polyfluorinated Polyether Compounds Impacting the Waters of Southwestern New Jersey Identified by Use of Nontargeted Analysis.” Environmental Science & Technology Letters 7 (12):903-908. 10.1021/acs.estlett.0c00640.

McCurdy, R. 2011. Underground Injection Wells for Produced Water Disposal. https://www.epa.gov/sites/default/files/documents/21_McCurdy_-_UIC_Disposal_508.pdf.

McDermett, Kaylin S., Jennifer Guelfo, Todd A. Anderson, Danny Reible, and Andrew W. Jackson. 2022. “The development of diffusive equilibrium, high-resolution passive samplers to measure perfluoroalkyl substances (PFAS) in groundwater.” Chemosphere 303:134686. https://doi.org/10.1016/j.chemosphere.2022.134686.

McDonough, Carrie A., Sarah Choyke, P. Lee Ferguson, Jamie C. DeWitt, and Christopher P. Higgins. 2020. “Bioaccumulation of Novel Per- and Polyfluoroalkyl Substances in Mice Dosed with an Aqueous Film-Forming Foam.” Environmental Science & Technology 54 (9):5700-5709. 10.1021/acs.est.0c00234.

McDonough, Carrie A., Jennifer L. Guelfo, and Christopher P. Higgins. 2019. “Measuring total PFASs in water: The tradeoff between selectivity and inclusivity.” Current Opinion in Environmental Science & Health 7:13-18. https://doi.org/10.1016/j.coesh.2018.08.005.

McDonough, Carrie A., Chastity Ward, Qing Hu, Samuel Vance, Christopher P. Higgins, and Jamie C. DeWitt. 2020. “Immunotoxicity of an Electrochemically Fluorinated Aqueous Film-Forming Foam.” Toxicological Sciences 178 (1):104-114. 10.1093/toxsci/kfaa138.

McDonough, J.T., R.H. Anderson, J.T. Lang, D. Liles, K. Matteson, and T. Olechiw. 2022. “Field-Scale Demonstration of PFAS Leachability Following In Situ Soil Stabilization.” ACS Omega 7 (1):419-429. https://doi.org/10.1021/acsomega.1c04789.

McDonough, Jeffrey T., John Kirby, Christopher Bellona, Joseph A. Quinnan, Nicklaus Welty, John Follin, and Ken Liberty. 2022. “Validation of supercritical water oxidation to destroy perfluoroalkyl acids.” Remediation Journal 32 (1-2):75-90. https://doi.org/10.1002/rem.21711.

McGregor, Rick. 2018. “In Situ treatment of PFAS-impacted groundwater using colloidal activated Carbon.” Remediation Journal 28 (3):33-41. 10.1002/rem.21558.

McGregor, R. 2020. “Distribution of Colloidal and Powdered Activated Carbon for the In Situ Treatment of Groundwater.” Journal of Water Resource and Protection 12:1001-1018. https://doi.org/10.4236/jwarp.2020.1212060.

McGregor, Rick. 2020. “Six pilot-scale studies evaluating the in situ treatment of PFAS in groundwater.” Remediation Journal 30 (3):39-50. https://doi.org/10.1002/rem.21653.

McGuire, M.E. 2013. An In-Depth Site Characterization of Poly- And Perfluoroalkyl Substances at an Abandoned Fire Protection Training Area. Master’s Thesis. Colorado School of Mines, Golden, CO.

McGuire, Meghan E., Charles Schaefer, Trenton Richards, Will J. Backe, Jennifer A. Field, Erika Houtz, David L. Sedlak, Jennifer L. Guelfo, Assaf Wunsch, and Christopher P. Higgins. 2014. “Evidence of Remediation-Induced Alteration of Subsurface Poly- and Perfluoroalkyl Substance Distribution at a Former Firefighter Training Area.” Environmental Science & Technology 48 (12):6644-6652. https://doi.org/10.1021/es5006187.

McIntyre, H.M. and M.L. Hart. 2021. Photocatalytic Porous Silica-Based Granular Media for Organic Pollutant Degradation in Industrial Waste-Streams. Catalysts, 11(2):258. https://Doi.org/10.3390/catal11020258.

McIntyre, H.M., V. Minda, E. Hawley, R. Deeb, and M.L. Hart. 2022. Coupled Photocatalytic Alkaline Media as a Destructive Technology for Per- and Polyfluoroalkyl Substances in Aqueous Film-Forming Foam Impacted Stormwater. Chemosphere, 291(1):132790. https://Doi.org/10.1016/j.chemosphere.2021.132790.

McIntyre, H.M., V. Minda, W. Gutheil, and M.L. Hart. 2021. Degradation and Defluorination of Aqueous Perfluorooctane Sulfonate by Silica-Based Granular Media Using Batch Reactors. Journal of Environmental Engineering, 147(11):04021048. https://Doi.org/10.1061/(ASCE)EE.1943-7870.00019220.

McIntyre, Hannah, Vidit Minda, Elisabeth Hawley, Rula Deeb, and Megan Hart. 2023. “Development and Laboratory Scalability of Ultraviolet-Activated Silica-Based Granular Media as an Engineered System for the Degradation of Per- and Polyfluoroalkyl Substances in Concentrated Liquid Waste.” Journal of Environmental Engineering 149 (9):04023049. https://Doi.org/10.1061/JOEEDU.EEENG-7228..

McKenzie, Erica, Robert L. Siegrist, John McCray, and Christopher Higgins. 2016. “The influence of a non-aqueous phase liquid (NAPL) and chemical oxidant application on perfluoroalkyl acid (PFAA) fate and transport.” Water Research 92:199-207. https://doi.org/10.1016/j.watres.2016.01.025.

McKenzie, Erica R., Robert L. Siegrist, John E. McCray, and Christopher P. Higgins. 2015. “Effects of Chemical Oxidants on Perfluoroalkyl Acid Transport in One-Dimensional Porous Media Columns.” Environmental Science & Technology 49 (3):1681-1689. https://doi.org/10.1021/es503676p.

McLennan, C. 2018. “New Science to Treat PFAS.” Katherine Times, Last Modified February 18, 2018. accessed 2021. https://www.katherinetimes.com.au/story/5234540/new-science-to-treat-pfas/.

McMurdo, Colin J., David A. Ellis, Eva Webster, Jessica Butler, Rebecca D. Christensen, and Liisa K. Reid. 2008. “Aerosol Enrichment of the Surfactant PFO and Mediation of the Water−Air Transport of Gaseous PFOA.” Environmental Science & Technology 42 (11):3969-3974. https://doi.org/10.1021/es7032026.

McNamara, J.D., R. Franco, R. Mimna, and L. Zappa. 2018. “Comparison of activated carbons for removal of perfluorinated compounds from drinking water.” Journal – American Water Works Association 110 (1):E2-E14. https://doi.org/10.5942/jawwa.2018.110.0003.

MDCH. 2014. Health Consultation: Technical Support Document for Assessment of Perfluorinated Chemicals and Selection of a Perfluorooctane Sulfonate (PFOS) Reference Dose as the basis for Michigan Fish Consumption Screening Values (FCSVs). Michigan Department of Community Health. http://www.michigan.gov/documents/mdch/MDCH_PFOS_Health_Consultation_2014_468766_7.pdf

MDCH. 2015. USEPA Great Lakes Restoration Initiative (GLRI) Project. Final Report. Michigan Department of Community Health. https://www.michigan.gov/documents/mdch/MDCH_GL-00E01122-0_Final_Report_493494_7.pdf.

MDH. 2008. Health Consultation – PFOS Detections in the City of Brainerd, Minnesota. Minnesota Department of Health. https://www.health.state.mn.us/communities/environment/hazardous/docs/pfas/pfosdetectbrainerd.pdf.

MDH. 2009. East Metro Perfluorochemical Biomonitoring Pilot Project. Minnesota Department of Health. https://www.health.state.mn.us/communities/environment/biomonitoring/docs/pfccomrpttocomm2009.pdf.

MDH. 2014. Evaluation of Point-of-use Water Treatment Devices for Perfluorochemical Removal. https://www.health.state.mn.us/communities/environment/hazardous/docs/poudevicefinalsummary.pdf.

MDH. 2017. MDH Current Activities: Perfluorochemicals (PFCs) in Minnesota, updated October 2017 http://www.health.state.mn.us/divs/eh/hazardous/topics/pfcs/201711pfosan.pdf

MDH. 2017. Toxicological Summary for: Perfluorbutane Sulfonate.

https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfbssummary.pdf

MDH. 2017. Toxicological Summary for: Perfluorooctane Sulfonate. Environmental Health Division Health Risk Assessment Unit.

MDH. 2017. Toxicological Summary for: Perfluorooctanoic Acid. Environmental Health Division Health Risk Assessment Unit.

MDH. 2018. Toxicological Summary for: Perfluorooctanoate. https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfoa.pdf.

MDH. 2018. Toxicological Summary for: Perfluorobutanoate. https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfba2summ.pdf.

MDH. 2019. Toxicological Summary for: Perfluorooctane Sulfonate. https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfos.pdf.

MDH. 2019. “Drinking Water Risk Communication Toolkit Tell Your Story – Connect with People.” Last Modified 3/20/2019. accessed 2020. https://www.health.state.mn.us/communities/environment/water/toolkit/story.html.

MDH. 2019. Perfluoroalkyl Substances and Health. St. Paul, MN: Minnesota Department of Health. https://www.health.state.mn.us/communities/environment/hazardous/docs/pfashealth.pdf.

MDH. 2020. Toxicological Summary for: Perfluorohexane Sulfonate (PFHxS). Health-Based Guidance for Water. Minnesota Department of Health. https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfhxs.pdf.

MDH. 2020. “Evaluating Concurrent Exposures to Multiple Chemicals.” Minnesota Department of Health. accessed 2021. https://www.health.state.mn.us/communities/environment/risk/guidance/gw/additivity.

MDH. 2021. Toxicological Summary for: Perfluorohexanoate (PFHxA). Health-Based Guidance for Water. Minnesota Department of Health. https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfhxa.pdf.

MDH. 2022. Toxicological Summary for: Perfluorobutane sulfonate (PFBS). Health-Based Guidance for Water. Minnesota Department of Health. https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfbssummary.pdf.

ME DEP. 2016. Maine Remedial Action Guidelines (RAGs) for Sites Contaminated with Hazardous Substances. Augusta, ME: Bureau of Remediation & Waste Management.

ME DEP. 2019. Memorandum: Requirement to analyze for PFAS compounds. State of Maine Department of Environmental Protection. https://www.maine.gov/dep/spills/topics/pfas/03222019_Sludge_Memorandum.pdf.

ME DEP. 2021. Maine PFAS Screening Levels. https://www.maine.gov/dep/spills/topics/pfas/Maine-PFAS-Screening-Levels-Rev-6.28.21.pdf.

ME DEP. 2021. Remedial Action Guidelines for Contaminated Sites. https://www.maine.gov/dep/spills/publications/guidance/rags/Maine-Remedial-Action-Guidelines-2021-05-01.pdf.

ME DEP. 2022. Background Levels of PFAS and PAHs in Main Shallow Soils. https://www.maine.gov/dep/spills/topics/pfas/Maine_Background_PFAS_Study_Report.pdf.

ME DIFW. 2023. “PFAS Do Not Eat Advisory.” Maine Department of Inland Fisheries & Wildlife. accessed 2023. https://www.maine.gov/ifw/hunting-trapping/hunting/laws-rules/pfas-related-consumption-advisory.html.

Mejia Avendaño, Sandra, and Jinxia Liu. 2015. “Production of PFOS from aerobic soil biotransformation of two perfluoroalkyl sulfonamide derivatives.” Chemosphere 119:1084-1090. https://doi.org/10.1016/j.chemosphere.2014.09.059.

Mejia-Avendaño, Sandra, Gabriel Munoz, Sébastien Sauvé, and Jinxia Liu. 2017. “Assessment of the Influence of Soil Characteristics and Hydrocarbon Fuel Cocontamination on the Solvent Extraction of Perfluoroalkyl and

Polyfluoroalkyl Substances." Analytical Chemistry 89 (4):2539-2546. 10.1021/acs.analchem.6b04746.

Mejia-Avendaño, Sandra, Sung Vo Duy, Sébastien Sauvé, and Jinxia Liu. 2016. "Generation of Perfluoroalkyl Acids from Aerobic Biotransformation of Quaternary Ammonium Polyfluoroalkyl Surfactants." Environmental Science & Technology 50 (18):9923-9932. 10.1021/acs.est.6b00140.

Mejia-Avendaño, Sandra, Yue Zhi, Bei Yan, and Jinxia Liu. 2020. "Sorption of Polyfluoroalkyl Surfactants on Surface Soils: Effect of Molecular Structures, Soil Properties, and Solution Chemistry." Environmental Science & Technology 54 (3):1513-1521. https://doi.org/10.1021/acs.est.9b04989.

Meng, Pingping, Shubo Deng, Ayiguli Maimaiti, Bin Wang, Jun Huang, Yujue Wang, Ian T. Cousins, and Gang Yu. 2018. "Efficient removal of perfluorooctane sulfonate from aqueous film-forming foam solution by aeration-foam collection." Chemosphere 203:263-270. https://doi.org/10.1016/j.chemosphere.2018.03.183.

Menger, Frank, Johannes Pohl, Lutz Ahrens, Gunnar Carlsson, and Stefan Örn. 2020. "Behavioural effects and bioconcentration of per- and polyfluoroalkyl substances (PFASs) in zebrafish (Danio rerio) embryos." Chemosphere 245:125573. https://doi.org/10.1016/j.chemosphere.2019.125573.

Merino, Nancy, Yan Qu, Rula A. Deeb, Elisabeth L. Hawley, Michael R. Hoffmann, and Shaily Mahendra. 2016. "Degradation and Removal Methods for Perfluoroalkyl and Polyfluoroalkyl Substances in Water." Environmental Engineering Science 33 (9):615-649. 10.1089/ees.2016.0233.

Mertens, J. J., D. W. Sved, G. B. Marit, N. R. Myers, P. L. Stetson, S. R. Murphy, B. Schmit, M. Shinohara, and C. H. Farr. 2010. "Subchronic toxicity of S-111-S-WB in Sprague Dawley rats." Int J Toxicol 29 (4):358-71. 10.1177/1091581810370372.

Messmer, Mindi F., Jeffrey Salloway, Nawar Shara, Ben Locwin, Megan W. Harvey, and Nora Traviss. 2022. "Risk of Cancer in a Community Exposed to Per- and Poly-Fluoroalkyl Substances." Environmental Health Insights 16:11786302221076707. 10.1177/11786302221076707.

Mhadhbi, Lazhar, Diego Rial, Sara Pérez, and Ricardo Beiras. 2012. "Ecological risk assessment of perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) in marine environment using Isochrysis galbana, Paracentrotus lividus, Siriella armata and Psetta maxima." Journal of Environmental Monitoring 14 (5):1375-1382. 10.1039/C2EM30037K.

MI DEQ. 2018. Wastewater PFAS Sampling Guidance. https://www.michigan.gov/documents/deq/deq-tou-wrd-WastewaterPFAS-Sampling_624506_7.pdf.

MI DEQ. 2018. General PFAS Sampling Guidance. https://www.michigan.gov/documents/pfasresponse/General_PFAS_Sampling_Guidance_634597_7.pdf.

MI DEQ. 2018. Reconnaissance sampling of perfluorinated compounds in Michigan surface waters and fish 2010-2014. Lansing, MI: Michigan Department of Environmental Quality.

DEQ, MI. 2018. Screening Level Derivation. Interoffice Communication. http://www.deq.state.mi.us/aps/downloads/ATSL/335-67-1/335-67-1_24hr_ITSL.pdf

MI DEQ. 2018. Surface Water PFAS Sampling Guidance. https://www.michigan.gov/documents/pfasresponse/Surface_Water_PFAS_Sampling_Guidance_639408_7.pdf.

MI DEQ. 2019. Fish Tissue PFAS Sampling Guidance. https://www.michigan.gov/documents/pfasresponse/Fish_Tissue_PFAS_Sampling_Guidance_644911_7.pdf.

MI DHHS. 2019. Public Health drinking water screening levels for PFAS. Division of Environmental Health Michigan Department of Health and Human Services.

MI DHHS. 2019. Technical Review Evaluating Recreational Exposure to Per- and Polyfluoroalkyl Substances (PFAS) in Van Etten Lake (Oscoda, MI) Surface water and foam. Lansing, MI: Michigan Department of Health and Human Services. https://www.michigan.gov/documents/pfasresponse/VEL_Surface_Water_and_Foam_LHC_-__21_May_2019_-__Final_655863_7.pdf.

MI DHHS. 2019. Van Etten Lake Surface Water and Foam Letter Health Consultation. Department of Health and Human Services State of Michigan. https://www.michigan.gov/documents/pfasresponse/VEL_Surface_Water_and_Foam_LHC_-__21_May_2019_-__Final_655863_7.pdf.

MI EGLE. 2019. “Rule 57 Water Quality Values.” Michigan Department of Environment, Great Lakes and Energy. accessed 2019. https://www.michigan.gov/egle/0,9429,7-135-3313_3681_3686_3728-11383–,00.html.

MI EGLE. 2019. Surface Water Foam PFAS Sampling Guidance. https://www.michigan.gov/documents/pfasresponse/Surface_Water_Foam_PFAS_Sampling_Guidance_+_Quick_Reference_Field_Guide_662168_7.pdf.

MI EGLE. 2020. Michigan Industrial Pretreatment Program PFAS Initiative. Identified Industrial Sources of PFOS to Municipal Wastewater Treatment Plants.

MI EGLE. 2020. Review of Available Software for PFAS Modeling within the Vadose Zone. Lansing, MI.

MI EGLE. 2021. “PFAS Sampling Guidance.” Michigan PFAS Response Team. accessed 2021. https://www.michigan.gov/pfasresponse/0,9038,7-365-88059_91297—,00.html.

MI EGLE. 2021. Surface Water Foam Study Report. https://www.michigan.gov/documents/pfasresponse/Surface_Water_Foam_Study_Report_-_AECOM_713003_7.pdf.

MI EGLE. 2022. Land Application of Biosolids Containing PFAS, Interim Strategy, Updated April 2022. https://www.michigan.gov/egle/about/organization/Water-Resources/biosolids/pfas-related.

MI ELGE. 2022. Biosolids and Sludge PFAS Sampling Guidance. www.michigan.gov/PFASResponse.

MI SAW. 2019. Health-Based Drinking Water Value Recommendations for PFAS in Michigan. Lansing, MI: Michigan Science Advisory Workgroup.

Miaz, Luc T., Merle M. Plassmann, Irina Gyllenhammar, Anders Bignert, Oskar Sandblom, Sanna Lignell, Anders Glynn, and Jonathan P. Benskin. 2020. “Temporal trends of suspect- and target-per/polyfluoroalkyl substances (PFAS), extractable organic fluorine (EOF) and total fluorine (TF) in pooled serum from first-time mothers in Uppsala, Sweden, 1996–2017.” Environmental Science: Processes & Impacts 22 (4):1071-1083. https://doi.org/10.1039/C9EM00502A.

Michalik, L., J. Auwerx, J. P. Berger, V. K. Chatterjee, C. K. Glass, F. J. Gonzalez, P. A. Grimaldi, T. Kadowaki, M. A. Lazar, S. O’Rahilly, C. N. Palmer, J. Plutzky, J. K. Reddy, B. M. Spiegelman, B. Staels, and W. Wahli. 2006. “International Union of Pharmacology. LXI. Peroxisome proliferator-activated receptors.” Pharmacol Rev 58 (4):726-41. https://doi.org/10.1124/pr.58.4.5.

Mikkonen, Antti T., Jennifer Martin, Richard N. Upton, Andrew O. Barker, Carolyn M. Brumley, Mark P. Taylor, Lorraine Mackenzie, and Michael S. Roberts. 2023. “Spatio-temporal trends in livestock exposure to per- and polyfluoroalkyl substances (PFAS) inform risk assessment and management measures.” Environmental Research 225:115518. https://doi.org/10.1016/j.envres.2023.115518.

Miklos, David B., Christian Remy, Martin Jekel, Karl G. Linden, Jörg E. Drewes, and Uwe Hübner. 2018. “Evaluation of advanced oxidation processes for water and wastewater treatment – A critical review.” Water Research 139:118-131. https://doi.org/10.1016/j.watres.2018.03.042.

Milinovic, J., S. Lacorte, M. Vidal, and A. Rigol. 2015. “Sorption behaviour of perfluoroalkyl substances in soils.” Science of The Total Environment 511:63-71. https://doi.org/10.1016/j.scitotenv.2014.12.017.

Mills, Marc A., D. Bless, K. Dasu, D.P. Siriwardena, and Dinal. A. 2020. “Thermal Treatment of PFAS in Environmental Media: A review of the state-of-the-science.” Thermal state of the Science, Cincinnati, OH, February 25, 2020 https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=348571&Lab=CESER.

Mimna, R. 2017. Reactivation of Activated Carbon for PFAS Removal. Calgon Memorandum.

Minata, M., K. H. Harada, A. Karrman, T. Hitomi, M. Hirosawa, M. Murata, F. J. Gonzalez, and A. Koizumi. 2010. “Role of peroxisome proliferator-activated receptor-alpha in hepatobiliary injury induced by ammonium perfluorooctanoate in mouse liver." Ind Health 48 (1):96-107. 10.2486/indhealth.48.96.

Miralles-Marco, Ana, and Stuart Harrad. 2015. "Perfluorooctane sulfonate: A review of human exposure, biomonitoring and the environmental forensics utility of its chirality and isomer distribution." Environment International 77:148-159. https://doi.org/10.1016/j.envint.2015.02.002.

Mitchell, Shannon M., Mushtaque Ahmad, Amy L. Teel, and Richard J. Watts. 2014. "Degradation of Perfluorooctanoic Acid by Reactive Species Generated through Catalyzed H2O2 Propagation Reactions." Environmental Science & Technology Letters 1 (1):117-121. 10.1021/ez4000862.

Miteni. 2016. Miteni-Company Profile-History. https://www.miteni.com.

Miyake, Yuichi, Nobuyoshi Yamashita, Pawel Rostkowski, Man Ka So, Sachi Taniyasu, Paul K. S. Lam, and Kurunthachalam Kannan. 2007. "Determination of trace levels of total fluorine in water using combustion ion chromatography for fluorine: A mass balance approach to determine individual perfluorinated chemicals in water." Journal of Chromatography A 1143 (1):98-104. https://doi.org/10.1016/j.chroma.2006.12.071.

Miyake, Yuichi, Nobuyoshi Yamashita, Man Ka So, Pawel Rostkowski, Sachi Taniyasu, Paul K. S. Lam, and Kurunthachalam Kannan. 2007. "Trace analysis of total fluorine in human blood using combustion ion chromatography for fluorine: A mass balance approach for the determination of known and unknown organofluorine compounds." Journal of Chromatography A 1154 (1):214-221. https://doi.org/10.1016/j.chroma.2007.03.084.

Miyata, K. 2007. Twenty-eight Day repeated Dose Oral Toxicity Study of the 13F-EtOH in Rats. (as cited by Rice et al. 2020). Japan: Hita Laboratory.

Moe, Morten K., Sandra Huber, Johan Svenson, An Hagenaars, Martial Pabon, Monika Trümper, Urs Berger, Dries Knapen, and Dorte Herzke. 2012. "The structure of the fire fighting foam surfactant Forafac®1157 and its biological and photolytic transformation products." Chemosphere 89 (7):869-875. https://doi.org/10.1016/j.chemosphere.2012.05.012.

Mogensen, Ulla B., Philippe Grandjean, Flemming Nielsen, Pal Weihe, and Esben Budtz-Jørgensen. 2015. "Breastfeeding as an Exposure Pathway for Perfluorinated Alkylates." Environmental Science & Technology 49 (17):10466-10473. 10.1021/acs.est.5b02237.

Mohammad Feisal, Rahman. 2015. Removal of Perfluorinated Compounds from Ultrapure and Surface Waters by Adsorption and Ion Exchange. Doctoral Dissertation. University of Waterloo, Waterloo, Ontario, Canada. http://hdl.handle.net/10012/9161.

Mok, Kira, Derrick Salvatore, Martha Powers, Phil Brown, Maddy Poehlein, Otakuye Conroy-Ben, and Alissa Cordner. 2022. "Federal PFAS Testing and Tribal Public Water Systems." Environmental Health Perspectives 130 (12):127701. 10.1289/EHP11652.

Molina, E. D., R. Balander, S. D. Fitzgerald, J. P. Giesy, K. Kannan, R. Mitchell, and S. J. Bursian. 2006. "Effects of air cell injection of perfluorooctane sulfonate before incubation on development of the white leghorn chicken (Gallus domesticus) embryo." Environ Toxicol Chem 25 (1):227-32.

Mommaerts, V., A. Hagenaars, J. Meyer, W. De Coen, L. Swevers, H. Mosallanejad, and G. Smagghe. 2011. "Impact of a perfluorinated organic compound PFOS on the terrestrial pollinator Bombus terrestris (Insecta, Hymenoptera)." Ecotoxicology 20 (2):447-56. 10.1007/s10646-011-0596-2.

Monnot, Andrew D., Andrey Massarsky, Lindsey Garnick, Suren B. Bandara, and Kenneth M. Unice. 2022. "Can oral toxicity data for PFAS inform on toxicity via inhalation?" Risk Analysis n/a (n/a). https://doi.org/10.1111/risa.14039.

Moodie, Damien, Timothy Coggan, Kathryn Berry, Adam Kolobaric, Milena Fernandes, Elliot Lee, Suzie Reichman, Dayanthi Nugegoda, and Bradley O. Clarke. 2021. "Legacy and emerging per- and polyfluoroalkyl substances (PFASs) in Australian biosolids." Chemosphere 270:129143. https://doi.org/10.1016/j.chemosphere.2020.129143.

Moody, Cheryl A., and Jennifer A. Field. 1999. "Determination of Perfluorocarboxylates in Groundwater Impacted by Fire-Fighting Activity." Environmental Science & Technology 33 (16):2800-2806. 10.1021/es981355+.

Moody, C. A., G. N. Hebert, S. H. Strauss, and J. A. Field. 2003. “Occurrence and persistence of perfluorooctanesulfonate and other perfluorinated surfactants in groundwater at a fire-training area at Wurtsmith Air Force Base, Michigan, USA.” J Environ Monit 5 (2):341-5.

Moody, Cheryl A., Jonathan W. Martin, Wai Chi Kwan, Derek C. G. Muir, and Scott A. Mabury. 2002. “Monitoring Perfluorinated Surfactants in Biota and Surface Water Samples Following an Accidental Release of Fire-Fighting Foam into Etobicoke Creek.” Environmental Science & Technology 36 (4):545-551. 10.1021/es011001+.

Morales-McDevitt, Maya E., Jitka Becanova, Arlene Blum, Thomas A. Bruton, Simon Vojta, Melissa Woodward, and Rainer Lohmann. 2021. “The Air That We Breathe: Neutral and Volatile PFAS in Indoor Air.” Environmental Science & Technology Letters 8 (10):897-902. 10.1021/acs.estlett.1c00481.

Morales-McDevitt, Maya E., Matthew Dunn, Ahsan Habib, Simon Vojta, Jitka Becanova, and Rainer Lohmann. 2022. “Poly- and Perfluorinated Alkyl Substances in Air and Water from Dhaka, Bangladesh.” Environmental Toxicology and Chemistry 41 (2):334-342. https://doi.org/10.1002/etc.5255.

Moreno, A.V.P. 2019. Modeling Atmospheric Transport of Perfluorinated Alkyl Substances from Chemours Facility Using CALPUFF View. Thesis in Partial Fulfillment of the Requirements for the Degree of Master of Science in the Graduate School of the Ohio State University. Columbus, OH. https://etd.ohiolink.edu/apexprod/rws_etd/send_file/send?accession=osu1555004834088189&disposition=inline.

Moriwaki, Hiroshi, Youichi Takagi, Masanobu Tanaka, Kenshiro Tsuruho, Kenji Okitsu, and Yasuaki Maeda. 2005. “Sonochemical Decomposition of Perfluorooctane Sulfonate and Perfluorooctanoic Acid.” Environmental Science & Technology 39 (9):3388-3392. 10.1021/es040342v.

Moriwaki, Hiroshi, Yumiko Takatah, and Arakawa Ryuichi. 2003. “Concentrations of perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) in vacuum cleaner dust collected in Japanese homes.” Journal of Environmental Monitoring (5):753-757. https://doi.org/10.1039/B307147M.

Morrison, R.D. 2000. Environmental Forensics: Principles & Applications. Boca Raton, FL: CRC Press. ISBN No. 0849320585.

Morrison, R.D., and B. Murphy. 2006. Environmental Forensics: Contaminant Specific Guide. Burlington, MA: Elsevier-Academic Press. ISBN No. 978-0125077514.

Moschet, Christoph, Bonny M. Lew, Simone Hasenbein, Tarun Anumol, and Thomas M. Young. 2017. “LC- and GC-QTOF-MS as Complementary Tools for a Comprehensive Micropollutant Analysis in Aquatic Systems.” Environmental Science & Technology 51 (3):1553-1561. https://doi.org/10.1021/acs.est.6b05352.

MPART. 2020. Perfluoroethylcyclohexane Sulfonfonate (PFECHS). Current Knowledge of Physicochemical Properties, Environmental Contamination and Toxicity. White Paper. Michigan PFAS Action Response Team (MPART) Human Health Workgroup (HHWG) and Michigan Department of Health and Human Services (MDHHS). https://www.michigan.gov/documents/pfasresponse/Current_Knowledge_of_Physiochemical_Properties_Environmental_Contamination_and_Toxicity_of_PFECHS_Whitepaper_702591_7.pdf.

MPART. 2023. “PFAS in Fish and Wildlife.” Michigan PFAS Action Response Team. accessed 2023. https://www.michigan.gov/pfasresponse/fishandwildlife.

MPART. 2023. “PFAS Foam on Lakes and Streams.” Last Modified June 27,2023. accessed 2023. https://www.michigan.gov/pfasresponse/investigations/lakes-and-streams/foam.

MPCA. 2007. Surface Water Quality Criterion for Perfluorooctane Sulfonic Acid. STS Project 200604796. St. Paul, MN: Minnesota Pollution Control Agency. https://www.pca.state.mn.us/sites/default/files/pfos-report.pdf.

MPCA. 2010. Aquatic Life Criteria and Water Quality Standards. St. Paul, MN: Minnesota Pollution Control Agency. https://www.pca.state.mn.us/sites/default/files/pfos-lakecalhoun.pdf.

MPCA. 2016. MPCA announces resolution of investigation in PFOS in Lake Calhoun.

MPCA. 2017. Perfluorochemical (PFC) Waste Sites.

https://www.epa.gov/sites/production/files/2017-02/documents/2016_pfoa_stewardship_summary_table_0.pdf

MPCA. 2020. Water Quality Standards Technical Support Document: Human Health Protective Water Quality Criteria for Perfluorooctane Sulfonate (PFOS). St. Paul, MN: Minnesota Pollution Control Agency. https://www.pca.state.mn.us/sites/default/files/wq-s6-61a.pdf.

MPCA. 2020. DRAFT Project 1007 Six-Month Investigation Progress Report, Appendix C – Preliminary Foam Assessment. Prepared by AECOM. https://3msettlement.state.mn.us/sites/3msettlement/files/Appendix%20C%20-%20Preliminary%20Foam%20Assessment_FullReport.pdf.

MPCA. 2020. Interim fish consumption rate for women of childbearing age. wq-s6-60. Saint Paul, MN: Minnesota Pollution Control Agency. https://www.pca.state.mn.us/sites/default/files/wq-s6-60.pdf.

MPCA. 2020. "PFAS foam on surface water." accessed 2021. https://www.pca.state.mn.us/waste/pfas-foam-surface-water.

MPCA. 2020. "PFAS-containing foam found in Washington and Ramsey counties." accessed 2023. https://content.govdelivery.com/accounts/MNPCA/bulletins/276d424.

MPCA. 2020. Project 1007 Six-Month Investigation Progress Report. https://3msettlement.state.mn.us/projects/project-1007.

MPCA. 2021. "Water Quality Standards." accessed 2021. https://www.pca.state.mn.us/water/water-quality-standards.

MPCA. 2022. Guidance for Per- and Polyfluoroalkyl substances (PFAS): Sampling. p-eao2-27. www.pca.state.mn.us.

MPCA. 2022. PFAS Air and Deposition Monitoring Report. https://www.pca.state.mn.us/sites/default/files/tdr-g1-23.pdf.

MPCA. 2022. Brainerd WWTP Permit. NPDES Permit MN0049328. https://webapp.pca.state.mn.us/wimn/site/1629/documents.

MPCA. 2023. "Minnesota 3M PFAS Settlement: Project 1007 ". accessed 2023. https://3msettlement.state.mn.us/projects/project-1007.

MPCA, MI EGLE, WI DNR. 2019. Foamy Friends Meeting Case Study Presentation Materials via Microsoft Teams. October 2019 – August 2020.

Mroczko, Olivia, Heather E. Preisendanz, Christopher Wilson, Michael L. Mashtare, Herschel A. Elliott, Tamie L. Veith, Kathy J. Soder, and John E. Watson. 2022. "Spatiotemporal patterns of PFAS in water and crop tissue at a beneficial wastewater reuse site in central Pennsylvania." Journal of Environmental Quality n/a (n/a). https://doi.org/10.1002/jeq2.20408.

Mudge, S.M. 2008. Methods in Environmental Forensics. Boca Raton: CRC Press. ISBN No. 9780429245244.

Mudumbi, J. B. N., S. K. O. Ntwampe, M. Muganza, and J. O. Okonkwo. 2014. "Susceptibility of Riparian Wetland Plants to Perfluorooctanoic Acid (PFOA) Accumulation." International Journal of Phytoremediation 16 (9):926-936. 10.1080/15226514.2013.810574.

Muensterman, Derek J., Liliana Cahuas, Ivan A. Titaley, Christopher Schmokel, Florentino B. De la Cruz, Morton A. Barlaz, Courtney C. Carignan, Graham F. Peaslee, and Jennifer A. Field. 2022. "Per- and Polyfluoroalkyl Substances (PFAS) in Facemasks: Potential Source of Human Exposure to PFAS with Implications for Disposal to Landfills." Environmental Science & Technology Letters 9 (4):320-326. 10.1021/acs.estlett.2c00019.

Mukerji, Pushkor, Jessica Caverly Rae, Robert C. Buck, and John C. O'Connor. 2015. "Oral repeated-dose systemic and reproductive toxicity of 6:2 fluorotelomer alcohol in mice." Toxicology Reports 2:130-143. https://doi.org/10.1016/j.toxrep.2014.12.002.

Müller, Claudia E., Amila O. De Silva, Jeff Small, Mary Williamson, Xiaowa Wang, Adam Morris, Sharon Katz, Mary Gamberg, and Derek C. G. Muir. 2011. "Biomagnification of Perfluorinated Compounds in a Remote Terrestrial Food Chain: Lichen–Caribou–Wolf." Environmental Science & Technology 45 (20):8665-8673. 10.1021/es201353v.

Mumtaz, M. M., M. C. Buser, and H. R. Pohl. 2021. “Per- and polyfluoroalkyl mixtures toxicity assessment “Proof-of-Concept” illustration for the hazard index approach.” Journal of Toxicology and Environmental Health, Part A 84 (13):553-567. 10.1080/15287394.2021.1901251.

Mundt, D. J., K. A. Mundt, R. S. Luippold, M. D. Schmidt, and C. H. Farr. 2007. “Clinical epidemiological study of employees exposed to surfactant blend containing perfluorononanoic acid.” Occup Environ Med 64 (9):589-94. 10.1136/oem.2007.032664.

Munoz, G., L. C. Fechner, E. Geneste, P. Pardon, H. Budzinski, and P. Labadie. 2018. “Spatio-temporal dynamics of per and polyfluoroalkyl substances (PFAS) and transfer to periphytic biofilm in an urban river: case-study on the River Seine.” Environmental Science and Pollution Research 25 (24):23574-23582.

Munoz, Gabriel, Jinxia Liu, Sung Vo Duy, and Sébastien Sauvé. 2019. “Analysis of F-53B, Gen-X, ADONA, and emerging fluoroalkylether substances in environmental and biomonitoring samples: A review.” Trends in Environmental Analytical Chemistry 23:e00066. https://doi.org/10.1016/j.teac.2019.e00066.

Munoz, Gabriel, Aurélia Marcelline Michaud, Min Liu, Sung Vo Duy, Denis Montenach, Camille Resseguier, Françoise Watteau, Valérie Sappin-Didier, Frédéric Feder, Thierry Morvan, Sabine Houot, Mélanie Desrosiers, Jinxia Liu, and Sébastien Sauvé. 2022. “Target and Nontarget Screening of PFAS in Biosolids, Composts, and Other Organic Waste Products for Land Application in France.” Environmental Science & Technology 56 (10):6056-6068. 10.1021/acs.est.1c03697.

Munoz, Gabriel, Aurélia Marcelline Michaud, Min Liu, Sung Vo Duy, Denis Montenach, Camille Resseguier, Françoise Watteau, Valérie Sappin-Didier, Frédéric Feder, Thierry Morvan, Sabine Houot, Mélanie Desrosiers, Jinxia Liu, and Sébastien Sauvé. 2022. “Target and Nontarget Screening of PFAS in Biosolids, Composts, and Other Organic Waste Products for Land Application in France.” Environmental Science & Technology 56 (10):6056-6068. 10.1021/acs.est.1c03697.

Murakami, Michio, Nozomi Adachi, Mahua Saha, Chiaki Morita, and Hideshige Takada. 2011. “Levels, Temporal Trends, and Tissue Distribution of Perfluorinated Surfactants in Freshwater Fish from Asian Countries.” Archives of Environmental Contamination and Toxicology 61 (4):631-641. https://doi.org/10.1007/s00244-011-9660-4.

Murphy, B., and R.D. Morrison. 2015. Introduction to Environmental Forensics. Third ed: Elsevier: Academic Press. ISBN No. 9780124049692.

Mussabek, Dauren, Lutz Ahrens, Kenneth M. Persson, and Ronny Berndtsson. 2019. “Temporal trends and sediment–water partitioning of per- and polyfluoroalkyl substances (PFAS) in lake sediment.” Chemosphere 227:624-629. https://doi.org/10.1016/j.chemosphere.2019.04.074.

Mussabek, Dauren, Kenneth M. Persson, Ronny Berndtsson, Lutz Ahrens, Kei Nakagawa, and Tomomi Imura. 2020. Impact of the Sediment Organic vs. Mineral Content on Distribution of the Per- and Polyfluoroalkyl Substances (PFAS) in Lake Sediment. International Journal of Environmental Research and Public Health 17 (16). 10.3390/ijerph17165642.

MWRA. 2019. Statewide Study on Landfill Leachate PFOA and PFOS Impact on Water Resource Recovery Facility Influent. Michigan Waste and Recycling Association. https://docs.wixstatic.com/ugd/6f7f77_5be8751a1f754474ac6e27fc8247eba2.pdf.

Mylchreest, Eve, Gregory S. Ladics, Susan M. Munley, Robert C. Buck, and Judith C. Stadler. 2005. “Evaluation of the Reproductive and Developmental Toxicity of a Fluoroalkylethanol Mixture.” Drug and Chemical Toxicology 28 (2):159-175. 10.1081/DCT-52518.

Mylchreest, E., S. M. Munley, and G. L. Kennedy. 2005. “Evaluation of the Developmental Toxicity of 8-2 Telomer B Alcohol.” Drug and Chemical Toxicology 28 (3):315-328. 10.1081/DCT-200064491.

Nabb, D. L., B. Szostek, M. W. Himmelstein, M. P. Mawn, M. L. Gargas, L. M. Sweeney, J. C. Stadler, R. C. Buck, and W. J. Fasano. 2007. “In vitro metabolism of 8-2 fluorotelomer alcohol: interspecies comparisons and metabolic pathway refinement.” Toxicol Sci 100 (2):333-44. 10.1093/toxsci/kfm230.

NACWA. 2023. Biosolids. Washington, D.C. https://www.nacwa.org/advocacy-analysis/campaigns/biosolids.

Naile, Jonathan E., Jong Seong Khim, Seongjin Hong, Jinsoon Park, Bong-Oh Kwon, Jong Seong Ryu, Jin Hwan Hwang, Paul D. Jones, and John P. Giesy. 2013. “Distributions and bioconcentration characteristics of perfluorinated compounds in environmental samples collected from the west coast of Korea.” Chemosphere 90 (2):387-394. https://doi.org/10.1016/j.chemosphere.2012.07.033.

Najm, I., B. Gallagher, N. Vishwanath, N. Blute, A. Gorzalski, A. Feffer, and S. Richardson. 2021. “Per- and polyfluoroalkyl substances removal with granular activated carbon and a specialty adsorbent: A case study.” AWWA Water Science e1245. https://doi.org/10.1002/aws2.1245.

Nakagawa, T., D. H. Ramdhan, N. Tanaka, H. Naito, H. Tamada, Y. Ito, Y. Li, Y. Hayashi, N. Yamagishi, Y. Yanagiba, T. Aoyama, F. J. Gonzalez, and T. Nakajima. 2012. “Modulation of ammonium perfluorooctanoate-induced hepatic damage by genetically different PPARalpha in mice.” Arch Toxicol 86 (1):63-74. 10.1007/s00204-011-0704-3.

NAS. 2021. Federal Government Human Health PFAS Research Workshop: Proceedings of a Workshop–in Brief. Washington, DC. https://www.nap.edu/catalog/26054/federal-government-human-health-pfas-research-workshop-proceedings-of-a.

NASEM. 2022. Guidance on PFAS Exposure, Testing, and Clinical Follow-Up. Washington, D.C.: The National Academies Press. https://doi.org/10.17226/26156.

Nason, Sara L., Jeremy Koelmel, Nubia Zuverza-Mena, Chelli Stanley, Carlos Tamez, John A. Bowden, and Krystal J. Godri Pollitt. 2021. “Software Comparison for Nontargeted Analysis of PFAS in AFFF-Contaminated Soil.” Journal of the American Society for Mass Spectrometry 32 (4):840-846. 10.1021/jasms.0c00261.

National Foam. 1996. Material Safety Data Sheet. http://www.kvfr.org/Assets/dept_1/pm/pdf/alcohol%20resistant%20aqueous%20film%20forming%20foam.pdf

National Research Council. 2009. Science and Decisions: Advancing Risk Assessment. Washington, DC: The National Academies Press. ISBN No. 978-0-309-12046-3. 10.17226/12209.

National Tribal Water Council. 2023. “Tribal PFAS Working Group.” accessed 2023. https://www7.nau.edu/itep/main/ntwc/Issues/PFAS.

Navarro, Irene, Adrián de la Torre, Paloma Sanz, Miguel Ángel Porcel, Javier Pro, Gregoria Carbonell, and María de los Ángeles Martínez. 2017. “Uptake of perfluoroalkyl substances and halogenated flame retardants by crop plants grown in biosolids-amended soils.” Environmental Research 152:199-206. https://doi.org/10.1016/j.envres.2016.10.018.

Navarro, Irene, Adrián de la Torre, Paloma Sanz, Javier Pro, Gregoria Carbonell, and María de los Ángeles Martínez. 2016. “Bioaccumulation of emerging organic compounds (perfluoroalkyl substances and halogenated flame retardants) by earthworm in biosolid amended soils.” Environmental Research 149:32-39. https://doi.org/10.1016/j.envres.2016.05.004.

NAVSEA. 2017. Performance Specification – Fire extinguishing agent, aqueous film-forming foam (AFFF) liquid concentrate for fresh and sea water. MIL-PRF-24385F(SH) with Amendment 2.

NC DEQ. 2018. Chemours Health Studies. https://edocs.deq.nc.gov/WaterResources/Browse.aspx?startid=624254&row=1&dbid=0

NC DEQ. 2018. “GenX Frequently Asked Questions.”. https://files.nc.gov/ncdeq/GenX/SAB/FAQ_updated_021518.pdf.

NC DEQ. 2019. “Air Quality Sampling.” accessed 2020. https://deq.nc.gov/news/key-issues/genx-investigation/air-quality-sampling.

NC DEQ. 2019. Chemours Weekly Rainwater Summary. https://files.nc.gov/ncdeq/GenX/Data/air-sampling/2019-04-09-Chemours-Weekly-Rainwater-summary.pdf.

NC DHHS. 2018. Biological sampling for GenX and other Per- and Polyfluoroalkyl Substances (PFAS) – North Carolina, 2018. North Carolina Dept. of Health and Human Services. https://epi.dph.ncdhhs.gov/oee/pfas/NCDHHS_PFAS%20Biomonitoring%20Report_8Nov2018.pdf.

NC DWR. 2022. Fact Sheet NPDES Permit No. NC0090042. North Carolina Division of Water Resources. https://deq.nc.gov/media/31345/download?attachment?attachment.

NCDENR. 2012. Memorandum. NCSAB Recommendation for the Revision of the IMAC for Perfluorooctanoic Acid (PFOA). Raleigh, NC: Division of Air Quality.

NEBRA. 2020. Sampling and Analysis of PFAS in Biosolids and Associated Media. Version 3.2. https://www.nebiosolids.org/pfas-sampling-analysis-guidance.

Negri, Eva, Francesca Metruccio, Valentina Guercio, Luca Tosti, Emilio Benfenati, Rossella Bonzi, Carlo La Vecchia, and Angelo Moretto. 2017. “Exposure to PFOA and PFOS and fetal growth: a critical merging of toxicological and epidemiological data.” Critical Reviews in Toxicology 47 (6):489-515. 10.1080/10408444.2016.1271972.

NEIWPCC. 2006. The Wastewater Treatment Plant Operators Guide to Biosolids Sampling Plans. New England Interstate Water Pollution Control Commission. https://neiwpcc.org/wp-content/uploads/2022/06/Wastewater-treatment-plant-operators-guide-to-biosolids-sampling-plans-2006.pdf.

NEMP. 2020. Australian and New Zealand (Heads of EPA, HEPA) PFAS National Environmental Management Plan, V2.

NEPC. 2013. National Environment Protection (Assessment of Site Contamination) Measure 1999. Volume 9. Schedule B6 Guideline On The Framework for Risk-Based Assessment of Groundwater Contamination: Federal Register of Legislative Instruments F2013C00288.

NEPI. 2000. Assessing the Bioavailability of Metals in Soil for Use in Human Health Risk Assessments. National Environmental Policy Institute.

New York State. 2017. Hazardous Substances Identification, Release Prohibition, and Release Reporting. http://www.dec.ny.gov/regulations/105074.html.

Newell, Charles J., David T. Adamson, Poonam R. Kulkarni, Blossom N. Nzeribe, John A. Connor, Jovan Popovic, and Hans F. Stroo. 2021. “Monitored Natural Attenuation to Manage PFAS Impacts to Groundwater: Scientific Basis.” Groundwater Monitoring & Remediation 41 (4):76-89. https://doi.org/10.1111/gwmr.12486.

Newell, Charles J., David T. Adamson, Poonam R. Kulkarni, Blossom N. Nzeribe, John A. Connor, Jovan Popovic, and Hans F. Stroo. 2021. “Monitored natural attenuation to manage PFAS impacts to groundwater: Potential guidelines.” Remediation Journal 31 (4):7-17. https://doi.org/10.1002/rem.21697.

Newell, Charles J., Hassan Javed, Yue Li, Nicholas W. Johnson, Stephen D. Richardson, John A. Connor, and David T. Adamson. 2022. “Enhanced attenuation (EA) to manage PFAS plumes in groundwater.” Remediation Journal 32 (4):239-257. https://doi.org/10.1002/rem.21731.

Newell, Charles J., Hassan Javed, Yue Li, Nicholas W. Johnson, Stephen D. Richardson, John A. Connor, and David T. Adamson. 2022. “Enhanced attenuation (EA) to manage PFAS plumes in groundwater.” Remediation Journal 32 (4):239-257. https://doi.org/10.1002/rem.21731.

Newman, P. 2022. “Foam Fractionation for PFAS Removal: Leveraging the Physiochemistry of PFAS Against Itself.” RemTech 2022 https://esaa.org/remtech/proceedings/2022-2/.

Newsted, John L., Susan A. Beach, Sean P. Gallagher, and John P. Giesy. 2006. “Pharmacokinetics and Acute Lethality of Perfluorooctanesulfonate (PFOS) to Juvenile Mallard and Northern Bobwhite.” Archives of Environmental Contamination and Toxicology 50 (3):411-420. https://doi.org/10.1007/s00244-005-1137-x.

Newsted, J. L., S. A. Beach, S. P. Gallagher, and J. P. Giesy. 2008. “Acute and chronic effects of perfluorobutane sulfonate (PFBS) on the mallard and northern bobwhite quail.” Arch Environ Contam Toxicol 54 (3):535-545. https://doi.org/10.1007/s00244-007-9039-8.

Newsted, J. L., K. K. Coady, S. A. Beach, J. L. Butenhoff, S. Gallagher, and J. P. Giesy. 2007. “Effects of perfluorooctane sulfonate on mallard and northern bobwhite quail exposed chronically via the diet.” Environ Toxicol Pharmacol 23 (1):1-9. https://doi.org/10.1016/j.etap.2006.04.008.

Newsted, J. L., P. D. Jones, K. K. Coady, and J. P. Giesy. 2005. “Avian Toxicity Reference Values for Perfluorooctane Sulfonate.” Environmental Science & Technology 39 (23):9357-9362. https://doi.org/10.1021/es050989v.

Newton, S., R. McMahen, J. A. Stoeckel, M. Chislock, A. Lindstrom, and M. Strynar. 2017. “Novel Polyfluorinated Compounds Identified Using High Resolution Mass Spectrometry Downstream of Manufacturing Facilities near Decatur, Alabama.” Environ Sci Technol 51 (3):1544-1552. https://doi.org/10.1021/acs.est.6b05330.

Ney, R.E. 1995. Fate and Transport of Organic Chemicals in the Environment: A Practical Guide, Second Edition. Rockville, MD: Abs Consulting. ISBN No. 0865874700.

NFPA. 2014. Standard on Selection, Care, and Maintenance of Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting. NFPA 1851. Quincy, MA. https://www.nfpa.org.

NFPA. 2016. Standard for Automotive Fire Apparatus. NFPA 1901. Quincy, MA. https://www.nfpa.org.

NFPA. 2016. Standard for Low-, Medium-, and High-Expansion Foam. NFPA 11. Quincy, MA. https://www.nfpa.org.

NFPA. 2017. Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems. NFPA 25. Quincy, MA. https://www.nfpa.org.

NFPA. 2019. Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems. NFPA 16. Quincy, MA. https://www.nfpa.org.

NFPA. 2020. Standard for Evaluating Aircraft Rescue and Fire-Fighting Foam Equipment. NFPA 412. Quincy, MA: National Fire Protection Association. https://www.nfpa.org.

NFPA. 2022. Standard on Foam Chemicals for Fires in Class A Fuels. NFPA 1150. Quincy, MA: National Fire Protection Association. www.nfpa.org.

NFPA Research Foundation. 2022. Firefighting Foams: Fire Service Roadmap. Quincy, MA: Fire Protection Research Foundation. https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Emergency-responders/RFFirefightingFoamsFireServiceRoadmap.pdf.

Ng, Carla A., and Konrad Hungerbuehler. 2015. “Exploring the Use of Molecular Docking to Identify Bioaccumulative Perfluorinated Alkyl Acids (PFAAs).” Environmental Science & Technology 49 (20):12306-12314. 10.1021/acs.est.5b03000.

Ng, Carla A., and Konrad Hungerbühler. 2013. “Bioconcentration of Perfluorinated Alkyl Acids: How Important Is Specific Binding?” Environmental Science & Technology 47 (13):7214-7223. 10.1021/es400981a.

Ng, Carla A., and Konrad Hungerbühler. 2014. “Bioaccumulation of Perfluorinated Alkyl Acids: Observations and Models.” Environmental Science & Technology 48 (9):4637-4648. 10.1021/es404008g.

Nguyen, Thi Minh Hong, Jennifer Bräunig, Kristie Thompson, Jack Thompson, Shervin Kabiri, Divina A. Navarro, Rai S. Kookana, Charles Grimison, Craig M. Barnes, Christopher P. Higgins, Michael J. McLaughlin, and Jochen F. Mueller. 2020. “Influences of Chemical Properties, Soil Properties, and Solution pH on Soil–Water Partitioning Coefficients of Per- and Polyfluoroalkyl Substances (PFASs).” Environmental Science & Technology 54 (24):15883-15892. 10.1021/acs.est.0c05705.

NGWA. 2017. Groundwater and PFAS: State of Knowledge and Practice. Westerville, OH: National Groundwater Association. https://www.ngwa.org/what-is-groundwater/groundwater-issues/Groundwater-and-PFAS.

NH DES. 2016. “New Hampshire Code of Administrative Rules. Chapter Env-A 1400 Regulated Toxic Air Pollutants.” https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/Env-A%201400.pdf.

NH DES. 2016. Status and trends of mercury in fish tissue in New Hampshire waterbodies, 1992–2016. Concord, NH: New Hampshire Department of Environmental Services. https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/r-wd-17-22.pdf.

NH DES. 2017. “On-line GIS application, PFAS Sampling Results.” New Hampshire Department of Environmental Services.

http://nhdes.maps.arcgis.com/apps/View/index.html?appid=66770bef141c43a98a445c54a17720e2andextent=-73.5743,42.5413,-69.6852,45.4489

NH DES. 2019. “Air Emissions Monitoring for Stationary Sources.” accessed 2020. https://www.des.nh.gov/onestop-navigation.

NH DES. 2019. Laboratory Testing Guidelines for Per- and Polyfluoroalkyl Substances (PFAS) at Waste Sites.

NH DES. 2019. Plan to Generate PFAS Surface Water Quality Standards. Concord, NH: New Hampshire Department of Environmental Services. https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/r-wd-19-30.pdf.

NH DES. 2020. “NH PFAS Investigation. Public Water System Results.” accessed 2020.

NH DHHS. 2015. Perfluorochemical (PFC) Testing Program: Summary of test results for children <12 y.o. New Hampshire Dept. of Health and Human Services.

NH DHHS. 2016. Pease PFC Blood Testing Program: April 2015 – October 2015. https://www.dhhs.nh.gov/sites/g/files/ehbemt476/files/documents/2021-11/pease-pfc-blood-testing.pdf.

NH DHHS. 2017. Summary of the New Hampshire Department of Health and Human Services’ Perfluorochemical (PFC) Blood Testing Program, 2016-2017.

NH DHHS. 2018. “Additional PFAS Resources.”

Nickelsen, M. G., and S.E. Woodard. 2017. A sustainable system and method for removing and concentrating per-and polyfluoroalkyl substances (PFAS) from water. edited by U.S. Patent and Trademark Office.

Nickerson, Anastasia, Andrew C. Maizel, Christopher I. Olivares, Charles E. Schaefer, and Christopher P. Higgins. 2021. “Simulating Impacts of Biosparging on Release and Transformation of Poly- and Perfluorinated Alkyl Substances from Aqueous Film-Forming Foam-Impacted Soil.” Environmental Science & Technology 55 (23):15744-15753. 10.1021/acs.est.1c03448.

Nickerson, Anastasia, Alix E. Rodowa, David T. Adamson, Jennifer A. Field, Poonam R. Kulkarni, John J. Kornuc, and Christopher P. Higgins. 2021. “Spatial Trends of Anionic, Zwitterionic, and Cationic PFASs at an AFFF-Impacted Site.” Environmental Science & Technology 55 (1):313-323. https://doi.org/10.1021/acs.est.0c04473.

Nickerson, Anastasia, Alix E. Rodowa, David T. Adamson, Jennifer A. Field, Poonam R. Kulkarni, John J. Kornuc, and Christopher P. Higgins. 2021. “Spatial Trends of Anionic, Zwitterionic, and Cationic PFASs at an AFFF-Impacted Site.” Environmental Science & Technology 55 (1):313-323. 10.1021/acs.est.0c04473.

NICNAS. 2018. Per- and poly-fluorinated substances (PFAS). Australian Government Department of Health. Australia Industrial Chemicals Introduction Scheme. https://www.industrialchemicals.gov.au/consumers-and-community/and-poly-fluorinated-substances-pfas.

Nielsen, C., and A. Jöud. 2021. “Susceptibility to COVID-19 after High Exposure to Perfluoroalkyl Substances from Contaminated Drinking Water: An Ecological Study from Ronneby, Sweden.” Int J Environ Res Public Health 18 (20). 10.3390/ijerph182010702.

Nielsen, C., Y. Li, M. Lewandowski, T. Fletcher, and K. Jakobsson. 2022. “Breastfeeding initiation and duration after high exposure to perfluoroalkyl substances through contaminated drinking water: A cohort study from Ronneby, Sweden.” Environ Res 207:112206. 10.1016/j.envres.2021.112206.

Nielsen, G., W. J. Heiger-Bernays, J. J. Schlezinger, and T. F. Webster. 2022. “Predicting the effects of per- and polyfluoroalkyl substance mixtures on peroxisome proliferator-activated receptor alpha activity in vitro.” Toxicology 465:153024. 10.1016/j.tox.2021.153024.

Nilsson, Helena, Anna Kärrman, Anna Rotander, Bert van Bavel, Gunilla Lindström, and Håkan Westberg. 2010. “Inhalation Exposure to Fluorotelomer Alcohols Yield Perfluorocarboxylates in Human Blood?” Environmental Science & Technology 44 (19):7717-7722. 10.1021/es101951t.

Nilsson, H., A. Karrman, A. Rotander, B. van Bavel, G. Lindstrom, and H. Westberg. 2013. “Professional ski waxers’ exposure to PFAS and aerosol concentrations in gas phase and different particle size fractions." Environ Sci Process Impacts 15 (4):814-22. 10.1039/c3em30739e.

Nilsson, Helena, Anna Kärrman, Anna Rotander, Bert van Bavel, Gunilla Lindström, and Håkan Westberg. 2013. "Biotransformation of fluorotelomer compound to perfluorocarboxylates in humans." Environment International 51:8-12. https://doi.org/10.1016/j.envint.2012.09.001.

Nilsson, H., A. Karrman, H. Westberg, A. Rotander, B. van Bavel, and G. Lindstrom. 2010. "A time trend study of significantly elevated perfluorocarboxylate levels in humans after using fluorinated ski wax." Environ Sci Technol 44 (6):2150-5. 10.1021/es9034733.

NIOSH. 2021. "Workplace Safety and Health Topics: Per- and polyfluoroalkyl substances (PFAS)." Centers for Disease Control and Prevention, Last Modified July 7, 2021. accessed 2021. https://www.cdc.gov/niosh/topics/pfas/default.html.

Niu, Junfeng, Yang Li, Enxiang Shang, Zesheng Xu, and Jinzi Liu. 2016. "Electrochemical oxidation of perfluorinated compounds in water." Chemosphere 146:526-538. https://doi.org/10.1016/j.chemosphere.2015.11.115.

Niu, Junfeng, Hui Lin, Chen Gong, and Xiaomin Sun. 2013. "Theoretical and Experimental Insights into the Electrochemical Mineralization Mechanism of Perfluorooctanoic Acid." Environmental Science & Technology 47 (24):14341-14349. 10.1021/es402987t.

Niu, Junfeng, Hui Lin, Jiale Xu, Hao Wu, and Yangyang Li. 2012. "Electrochemical Mineralization of Perfluorocarboxylic Acids (PFCAs) by Ce-Doped Modified Porous Nanocrystalline PbO2 Film Electrode." Environmental Science & Technology 46 (18):10191-10198. 10.1021/es302148z.

NJDEP. 2014. Occurrence of Perfluorinated Chemicals in Untreated New Jersey Drinking Water Sources. New Jersey Department of Environmental Protection.

NJDEP. 2014. Establishing Dialogue: Planning for Successful Environmental Management. K. K. Pflugh, J. A. Shaw, and B. B. Johnson. Trenton, NJ: New Jersey Department of Environmental Protection. Division of Science and Research. https://hdl.handle.net/10929/111769.

NJDEP. 2018. Investigation of levels of perfluorinated compounds in New Jersey fish, surface water, and sediment (Updated 4/8/2019). SR15-010: Division of Science New Jersey Department of Environmental Protection, Research, and Environmental Health.

NJDEP. 2021. Technical Support Document: Interim Specific Groundwater Quality Criterion for Chloroperfluoropolyether Carboxylates (CAS Numbers 220182-27-4, 220207-15-8, 330809-92-2, and 329238-24-6) (Public Version). https://www.nj.gov/dep/dsr/supportdocs/ClPFPECAs-tsd.pdf.

NJDEP. 2022. Interim Soil, Soil Leachate, and Indoor Air Criteria, Reporting Limits, and Remediation Standards. https://nj.gov/dep/srp/guidance/rs/interim_soil_ia_rl_rs.html.

NJDWQI. 2015. Health-Based Maximum Contaminant Level Support Document: Perfluorononanoic Acid (PFNA). New Jersey Drinking Water Quality Institute. http://www.nj.gov/dep/watersupply/pdf/pfna-health-effects.pdf

NJDWQI. 2017. Maximum Contaminant Level Recommendation for Perfluorooctanoic Acid in Drinking Water, Basis and Background. Appendices A, B, C and D. New Jersey Drinking Water Quality Institute.

NJDWQI. 2017. Health-Based Maximum Contaminant Level Support Document: Perfluorooctanoic Acid (PFOA). New Jersey Drinking Water Quality Institute. https://www.nj.gov/dep/watersupply/pdf/pfoa-appendixa.pdf.

NJDWQI. 2017. Maximum Contaminant Level Recommendation for Perfluorooctanoic Acid in Drinking Water, Basis and Background. New Jersey Drinking Water Quality Institute.

NJDWQI. 2018. Health-Based Maximum Contaminant Level Support Document: Perfluorooctane Sulfonate (PFOS). New Jersey Drinking Water Quality Institute. http://www.nj.gov/dep/watersupply/pdf/pfos-recommendation-appendix-a.pdf

NJDWQI. 2018. Maximum Contaminant Level Recommendation for Perfluorooctane Sulfonate in Drinking Water. New Jersey Drinking Water Quality Institute.

NJDWQI. 2023. Review of Interim USEPA Health Advisories for PFOA and PFOS and Other Relevant Information. https://www.state.nj.us/dep/watersupply/pdf/dwqi-health-effects-pfas-report.pdf.

Noker, P. E. 2001. A pharmacokinetic study of potassium perfluorohexanoate in the cynomolgus monkey. Southern Research Institute.

Norden, M., U. Berger, and M. Engwall. 2016. “Developmental toxicity of PFOS and PFOA in great cormorant (Phalacrocorax carbo sinensis), herring gull (Larus argentatus) and chicken (Gallus gallus domesticus).” Environ Sci Pollut Res Int 23 (11):10855-10862. 10.1007/s11356-016-6285-1.

Nowack, K. 2017. GAC Treatment for PFC Removal. AWWA Webinar Program: Perfluorinated Compounds: Research and Treatment Part I.

NPCA. 2006. Økotoksikologiske effekter av PFOS, PFOA og 6:2 FTS på meitemark (Eisenia fetida) [Ecotoxicological effects of PFOS, PFOA and 6:2 FTS in earthworms]. edited by Statens foru-rensningstilsyn (SFT). Norway.

NPCA. 2008. Screening of Polyfluorinated Organic Compounds at Four Fire Training Facilities in Norway. TA-2444/2008: Norwegian Pollution Control Authority.

NSF. 2019. “PFOA/PFOS Reduction Claims Requirements Added to NSF Standards for Drinking Water Treatment Devices.” accessed 2023. https://www.nsf.org/news/pfoa-pfos-reduction-claims-requirements-added-to-nsf-standards.

NSF. 2021. “PFOA/PFOS in Drinking Water.” National Sanitation Foundation (NSF), Last Modified July 2021. accessed 2023. https://www.nsf.org/consumer-resources/articles/pfoa-pfos-drinking-water.

NTP. 2016. NTP Monograph on Immunotoxicity Associated with Exposure to Perfluorooctanoic Acid (PFOA) or Perfluorooctane Sulfonate (PFOS). Division of the National Toxicology Program Office of Health Assessment and Translation, National Institute of Environmental Health Sciences. https://ntp.niehs.nih.gov/ntp/ohat/pfoa_pfos/pfoa_pfosmonograph_508.pdf

NTP. 2018. Fluorotelomer alcohol 8+2 (678-39-7). Study Results. Genetic Toxicology. National Toxicology Program. U. S. Department of Health and Human Services. https://manticore.niehs.nih.gov/cebssearch/test_article/678-39-7.

NTP. 2019. NTP Technical Report on the Toxicity Studies of Perfluoroalkyl Carboxylates (Perfluorohexanoic Acid, Perfluorooctanoic Acid, Perfluorononanoic Acid and Perfluorodecanoic Acid) Administered by Gavage to Sprague Dawley (HSD: Sprague Dawley SD) Rats. NTP TOX 97: National Toxicology Program. U. S. Department of Health and Human Services. https://ntp.niehs.nih.gov/publications/reports/tox/000s/tox097/index.html.

NTP. 2019. NTP Technical Report on the Toxicity Studies of Perfluoroalkyl Sulfonates (Perfluorobutane Sulfonic Acid, Perfluorohexane Sulfonate Potassium Salt, and Perfluorooctane Sulfonic Acid) Administered by Gavage to Sprague Dawley (HSD: Sprague Dawley SD) Rats. NTP TOX 96: National Toxicology Program. U. S. Department of Health and Human Services. https://ntp.niehs.nih.gov/publications/reports/tox/000s/tox096/index.html.

NTP. 2020. NTP Technical Report on the Toxicology and Carcinogenesis Studies of Perfluorooctanoic Acid (CAS No. 335-67-1) Administered in Feed to Sprague Dawley (Hsd: Sprague Dawley SD) Rats. Technical Report 598. Research Triangel Park, NC: National Toxicology Program. U. S. Department of Health and Human Services. https://ntp.niehs.nih.gov/ntp/htdocs/lt_rpts/tr598_508.pdf.

NTP. 2022. NTP technical report on the toxicity studies of perfluoroalkyl sulfonates (perfluorobutane sulfonic acid, perfluorohexane sulfonate potassium salt, and perfluorooctane sulfonic acid) administered by gavage to Sprague Dawley (Hsd:Sprague Dawley SD) rats (revised). Toxicity Report 96. Research Triangle Park, NC: National Toxicology Program. https://doi.org/10.22427/NTP-TOX-96.

NTP. 2022. NTP technical report on the toxicity studies of perfluoroalkyl carboxylates (perfluorohexanoic acid, perfluorooctanoic acid, perfluorononanoic acid, and perfluorodecanoic acid) administered by gavage to Sprague Dawley (Hsd:Sprague Dawley SD) rats (revised). Toxicity Report 97. Research Triangle Park, NC: National Toxicology Program. https://doi.org/10.22427/NTP-TOX-97.

NY DEC. 2016. Stewart Ang Base and Newburgh Watershed Investigation Report.

https://www.dec.ny.gov/data/DecDocs/336089/.

NY DEC. 2017. Adoption of Final Rule: 6NYCRR Part 597. http://www.dec.ny.gov/regulations/104968.html

NY DEC. 2017. “Petersburgh. Information for Communities Impacted by Perfluorinated Compounds (PFCs).” http://www.dec.ny.gov/chemical/108820.html

NY DEC. 2021. Sampling, Analysis, and Assessment of Per-and Polyfluoroalkyl Substances (PFAS). Under NYSDEC’s Part 375 Remedial Programs.

NY DEC. 2021. Norlite Environmental Sampling Report. Albany, NY: New York State Department of Environmental Conservation. https://www.dec.ny.gov/chemical/121118.html.

NY DEC. 2022. Sampling, Analysis, and Assessment of Per- and Polyfluoroalkyl Substances (PFAS) Under NYSDEC’s Part 375 Remedial Programs. https://www.dec.ny.gov/docs/remediation_hudson_pdf/pfassampanaly.pdf.

NYS DOH. 2016. Village of Hoosick Falls and Town of Hoosick Private Well Sampling, Perfluorooctanoic Acid (PFOA) Results Map – Updated August 3, 2016. New York State Department of Health. http://www.villageofhoosickfalls.com/Water/Documents/NYSDOH-TestingResultsMap-08092016.png

NYS DOH. 2016. Information Sheet. PFOA Biomonitoring Group Level Results. https://www.health.ny.gov/environmental/investigations/drinkingwaterresponse/docs/final_group_results.pdf.

Nzeribe, Blossom Nwedo, Michelle Crimi, Selma Mededovic Thagard, and Thomas M. Holsen. 2019. “Physico-Chemical Processes for the Treatment of Per- And Polyfluoroalkyl Substances (PFAS): A review.” Critical Reviews in Environmental Science and Technology 49 (10):866-915. 10.1080/10643389.2018.1542916.

O’Fallon, L. R., F. L. Tyson, and A Dearry. 2000. Successful Models of Community-Based Participatory Research: Final Report. Research Triangle Park, NC: National Institute of Environmental Health Sciences.

O’Connor, John C., Susan M. Munley, Tessa L. Serex, and Robert C. Buck. 2014. “Evaluation of the reproductive and developmental toxicity of 6:2 fluorotelomer alcohol in rats.” Toxicology 317:6-16. https://doi.org/10.1016/j.tox.2014.01.002.

O’Haire, C., M. McPheeters, E. Nakamoto, L. LaBryant, C. Most, K. Lee, E. Graham, E. Cottrell, and J-M. Guise. 2011. Engaging Stakeholders to Identify and Prioritize Future Research Needs. Methods Future Research Needs Reports, No. 4. Appendix F, Descriptions of Stakeholder Engagement Methods. Rockville, MD: Agency for Healthcare Research and Quality. Available from: https://www.ncbi.nlm.nih.gov/books/NBK62556/.

Oakes, K.D., P.K. Sibley, J.W. Martin, D.D. MacLean, K.R. Solomon, S.A. Mabury, and G.J. Van Der Kraak. 2005. “Short-term exposures of fish to perfluorooctane sulfonate: Acute effects on fatty acyl-CoA oxidase activity, oxidative stress, and circulating sex steroids.” Environ Contam Toxicol 24 (5):1172-1181. 10.1897/04-419.1.

Obo, Hayato, Nozomi Takeuchi, and Koichi Yasuoka. 2015. “Decomposition of Perfluoro Compounds using Plasmas within Bubbles in Water and Simulation of Decomposition System by Circuit Modeling of Plasma.” IEEJ Transactions on Fundamentals and Materials 135 (5):310-317. https://doi.org/10.1541/ieejfms.135.310.

Ochiai, Tsuyoshi, Yuichi Iizuka, Kazuya Nakata, Taketoshi Murakami, Donald A. Tryk, Akira Fujishima, Yoshihiro Koide, and Yuko Morito. 2011. “Efficient electrochemical decomposition of perfluorocarboxylic acids by the use of a boron-doped diamond electrode.” Diamond and Related Materials 20 (2):64-67. https://doi.org/10.1016/j.diamond.2010.12.008.

Ochoa-Herrera, V., J. A. Field, A. Luna-Velasco, and R. Sierra-Alvarez. 2016. “Microbial toxicity and biodegradability of perfluorooctane sulfonate (PFOS) and shorter chain perfluoroalkyl and polyfluoroalkyl substances (PFASs).” Environ Sci Process Impacts 18 (9):1236-1246. 10.1039/c6em00366d.

Ochoa-Herrera, Valeria, and Reyes Sierra-Alvarez. 2008. “Removal of perfluorinated surfactants by sorption onto granular activated carbon, zeolite and sludge.” Chemosphere 72 (10):1588-1593. https://doi.org/10.1016/j.chemosphere.2008.04.029.

Ochoa-Herrera, Valeria, Reyes Sierra-Alvarez, Arpad Somogyi, Neil E. Jacobsen, Vicki H. Wysocki, and Jim A. Field. 2008.

"Reductive Defluorination of Perfluorooctane Sulfonate." Environmental Science & Technology 42 (9):3260-3264. 10.1021/es702842q.

OECD. 2002. Hazard assessment of perfluorooctane sulfonate (PFOS) and its salts. ENV/JM/RD (2002)17/FINAL. Paris: Pesticides Joint Meeting of the Chemicals Committee and the Working Party on Chemicals, and Biotechnology, Environment Directorate, Organisation for Economic Co-operation and Development. http://www.oecd.org/dataoecd/23/18/2382880.pdf.

OECD. 2006. Results of the 2006 Survey on Production and Use of PFOS, PFAS, PFOA, PFCA, Their Related Substances and Products/Mixtures Containing These Substances. ENV-JM-MONO(2006)36. Paris: Organisation for Economic Co-operation and Development. http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=env/jm/mono(2006)36

OECD. 2007. Report of an OECD Workshop on Perfluorocarboxylic Acids (PFCAs) and Precursors. ENV-JM-MONO(2007)11. Paris: Organisation for Economic Co-operation and Development.

OECD. 2007. Guidance on Grouping of Chemicals, Second Edition. No. 194. Paris: OECD Series on Testing and Assessment. https://doi.org/10.1787/9789264274679-en.

OECD. 2011. PFCS: Outcome of the 2009 Survey – Survey on the Production, Use and Release of PFOS, PFAS, PFOA, PFCA, Their Related Substances and Products/Mixtures Containing These Substances. ENV-JM-MONO(2011)1. Paris: Organisation for Economic Co-operation and Development. http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=env/jm/mono(2011)1&doclanguage=en.

OECD. 2012. OECD Guidelines for Testing of Chemicals: Bioaccumulation in Fish: Aqueous and Dietary Exposure. Test No. 305: Organisation for Economic Co-operation and Development. https://www.oecd-ilibrary.org/environment/test-no-305-bioaccumulation-in-fish-aqueous-and-dietary-exposure_9789264185296-en.

OECD. 2013. OECD/UNEP Global PFC Group, Synthesis paper on per- and polyfluorinated chemicals (PFCs). Paris: Health and Safety Environment, Environment Directorate, OECD. https://www.oecd.org/env/ehs/risk-management/PFC_FINAL-Web.pdf

OECD. 2015. Risk Reduction Approaches for PFASs – a Cross-Country Analysis. Paris: OECD Environment Directorate. http://www.oecd.org/chemicalsafety/risk-management/Risk_Reduction_Approaches%20for%20PFASS.pdf.

OECD. 2015. Working Towards a Global Emission Inventory of PFASs: Focus on PFCAs – Status Quo and the Way Forward. No. 30. Paris: OECD Environment Directorate. https://tinyurl.com/3shcbydk.

OECD. 2017. "Portal on Per and Poly Fluorinated Chemicals." accessed 2017. http://www.oecd.org/chemicalsafety/portal-perfluorinated-chemicals/.

OECD. 2018. Toward a New Comprehensive Global Database of Per- And Polyfluoroalkyl Substances (PFASs): Summary Report on Updating the OECD 2007 List of Per- and Polyfluoroalkyl Substances (PFASs) ENV/JM/MONO(2018)7. Paris: Health and Safety Division Environment, OECD. https://www.oecd.org/chemicalsafety/portal-perfluorinated-chemicals/.

OECD. 2021. Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance. No. 61. Paris: OECD Publishing. https://www.oecd.org/chemicalsafety/portal-perfluorinated-chemicals/terminology-per-and-polyfluoroalkyl-substances.pdf.

Ohmori, K., N. Kudo, K. Katayama, and Y. Kawashima. 2003. "Comparison of the toxicokinetics between perfluorocarboxylic acids with different carbon chain length." Toxicology 184 (2-3):135-40.

Ojo, A. F., C. Peng, P. Annamalai, M. Megharaj, and J. C. Ng. 2022. "Toxicity assessment of historical aqueous film-forming foams (AFFFs) using cell-based assays." Environ Pollut 310:119806. 10.1016/j.envpol.2022.119806.

Ojo, Atinuke F., Cheng Peng, and Jack C. Ng. 2020. "Combined effects and toxicological interactions of perfluoroalkyl and polyfluoroalkyl substances mixtures in human liver cells (HepG2)." Environmental Pollution 263:114182.

https://doi.org/10.1016/j.envpol.2020.114182.

Oliaei, F., K. Kessler, and D. Kriens. 2006. Investigation of Perfluorochemical (PFC) Contamination in Minnesota Phase One. Report to Senate Environment Committee. https://peer.org/wp-content/uploads/attachments/06_27_2_pfc_report.pdf.

Oliaei, F., D. Kriens, and R. Weber. 2010. “Discovery and Investigation of PFOS/PFCs Contamination from a PFC Manufacturing Facility in Minnesota – Environmental Releases and Exposure Risks.” Organohalogen Compounds 72:1338-1341.

Oliaei, Fardin, Don Kriens, Roland Weber, and Alan Watson. 2013. “PFOS and PFC releases and associated pollution from a PFC production plant in Minnesota (USA).” Environmental Science and Pollution Research 20 (4):1977-1992. 10.1007/s11356-012-1275-4.

Olker, J.H. 2020. Update on Identification and Curation of Ecological Toxicity Data for PFAS with the ECOTOXicology Knowledgebase Protocols. Presentation. USEPA Center for Computational Toxicology and Exposure.

Ololade, Isaac Ayodele. 2014. “Hysteretic Desorption of Perfluorooctane Sulphonates within Sediment Components under Aerobic and Anoxic Conditions.” International Research Journal of Pure and Applied Chemistry 4:773-784.

Olsen Geary, W., Han-Yao Huang, J. Helzlsouer Kathy, J. Hansen Kristen, L. Butenhoff John, and H. Mandel Jeffrey. 2005. “Historical Comparison of Perfluorooctanesulfonate, Perfluorooctanoate, and Other Fluorochemicals in Human Blood.” Environmental Health Perspectives 113 (5):539-545. 10.1289/ehp.7544.

Olsen, G. W. 2015. “PFAS biomonitoring in higher exposed populations.” In Toxicological Effects of Perfluoroalkyl and Polyfluoroalkyl Substances, edited by J.D. DeWitt, 77-126. Humana Press. ISBN No. 978-3-319-15517-3.

Olsen, G. W., M. M. Burlew, J. C. Marshall, J. M. Burris, and J. H. Mandel. 2004. “Analysis of episodes of care in a perfluorooctanesulfonyl fluoride production facility.” J Occup Environ Med 46 (8):837-46.

Olsen, G. W., J. M. Burris, M. M. Burlew, and J. H. Mandel. 2003. “Epidemiologic assessment of worker serum perfluorooctanesulfonate (PFOS) and perfluorooctanoate (PFOA) concentrations and medical surveillance examinations.” J Occup Environ Med 45 (3):260-70.

Olsen, G. W., J. M. Burris, D. J. Ehresman, J. W. Froehlich, A. M. Seacat, J. L. Butenhoff, and L. R. Zobel. 2007. “Half-life of serum elimination of perfluorooctane sulfonate,perfluorohexane sulfonate, and perfluorooctanoate in retired fluorochemical production workers.” Environ Health Perspect 115 (9):1298-305. https://doi.org/10.1289/ehp.10009.

Olsen, G. W., S. C. Chang, P. E. Noker, G. S. Gorman, D. J. Ehresman, P. H. Lieder, and J. L. Butenhoff. 2009. “A comparison of the pharmacokinetics of perfluorobutane sulfonate (PFBS) in rats, monkeys, and humans.” Toxicology 256 (1-2):65-74. https://doi.org/10.1016/j.tox.2008.11.008.

Olsen, Geary W., Timothy R. Church, John P. Miller, Jean M. Burris, Kristen J. Hansen, James K. Lundberg, John B. Armitage, Ross M. Herron, Zahra Medhdizadehkashi, John B. Nobiletti, E. Mary O’Neill, Jeffrey H. Mandel, and Larry R. Zobel. 2003. “Perfluorooctane sulfonate and other fluorochemicals in the serum of American Red Cross adult blood donors.” Environmental health perspectives 111 (16):1892-1901. https://doi.org/10.1289/ehp.6316.

Olsen, Geary W., David C. Mair, Cleston Lange, Laura M. Harrington, Timothy Church, Corinne L. Goldberg, Ross Herron, Hank Hanna, John B. Nobiletti, Jorge A. Rios, William K. Reagen, and Carol A. Ley. 2017. “Per- and polyfluoroalkyl substances (PFAS) in American Red Cross adult blood donors, 2000-2015.” Environmental Research 157:87-95. https://doi.org/10.1016/j.envres.2017.05.013.

Olsen, G. W., and L. R. Zobel. 2007. “Assessment of lipid, hepatic, and thyroid parameters with serum perfluorooctanoate (PFOA) concentrations in fluorochemical production workers.” Int Arch Occup Environ Health 81 (2):231-46. 10.1007/s00420-007-0213-0.

Olson, C. T., and M. E. Andersen. 1983. “The acute toxicity of perfluorooctanoic and perfluorodecanoic acids in male rats and effects on tissue fatty acids.” Toxicol Appl Pharmacol 70 (3):362-72.

Onishchenko, Natalia, Celia Fischer, Wan Norhamidah Wan Ibrahim, Sara Negri, Stefan Spulber, Danilo Cottica, and

Sandra Ceccatelli. 2011. “Prenatal Exposure to PFOS or PFOA Alters Motor Function in Mice in a Sex-Related Manner.” Neurotoxicity Research 19 (3):452-461. 10.1007/s12640-010-9200-4.

OSHA. 2013. Fact Sheet: Controlling Hexavalent Chromium Exposures during Electroplating. United States Department of Labor.

Ostertag, Sonja K., Brett A. Tague, Murray M. Humphries, Sheryl A. Tittlemier, and Hing Man Chan. 2009. “Estimated dietary exposure to fluorinated compounds from traditional foods among Inuit in Nunavut, Canada.” Chemosphere 75 (9):1165-1172. https://doi.org/10.1016/j.chemosphere.2009.02.053.

Otto, M. 2016. Chemometrics: Statistics and Computer Application in Analytical Chemistry. Third ed. ISBN No. 978-3-527-34097-2.

Pachkowski, B., G. B. Post, and A. H. Stern. 2019. “The derivation of a Reference Dose (RfD) for perfluorooctane sulfonate (PFOS) based on immune suppression.” Environ Res 171:452-469. 10.1016/j.envres.2018.08.004.

Padilla-Sánchez, Juan A., Eleni Papadopoulou, Somrutai Poothong, and Line S. Haug. 2017. “Investigation of the Best Approach for Assessing Human Exposure to Poly- and Perfluoroalkyl Substances through Indoor Air.” Environmental Science & Technology 51 (21):12836-12843. 10.1021/acs.est.7b03516.

Palma-Oliveira, José, and Rui Gaspar. 2004. Environmental education programs construction: some conceptual and evaluation guidelines. Lisboa: Universidade de Lisboa.

Palmer, S. J., and H. O. Krueger. 2001. PFOS: A frog embryo teratogenesis assay-Xenopus(FETAX). Project No. 454A-116, EPA Docket AR226-1030a057: Wildlife International Ltd.

Palmer, S.J., R.L. Van Hoven, and H.O. Krueger. 2002. Perfluorooctanesulfonate, potassium salt (PFOS): a 96-hr static acute toxicity test with the rainbow trout (Oncorhynchus mykiss). Report No. 454A-145, EPA Docket AR226-1030a044: Wildlife International Ltd.

Palmer, S. J., R. L. Van Hoven, and H. O. Krueger. 2002. Perfluorooctanesulfonate, potassium salt (PFOS): a 96-hr static renewal acute toxicity test with the sheepshead minnow (Cyprinodon variegatus). Report No. 454A-146A: Wildlife International Ltd.

Pan, Chang-Gui, Guang-Guo Ying, You-Sheng Liu, Qian-Qian Zhang, Zhi-Feng Chen, Feng-Jiao Peng, and Guo-Yong Huang. 2014. “Contamination profiles of perfluoroalkyl substances in five typical rivers of the Pearl River Delta region, South China.” Chemosphere 114:16-25. https://doi.org/10.1016/j.chemosphere.2014.04.005.

Pan, Chang-Gui, Guang-Guo Ying, Jian-Liang Zhao, You-Sheng Liu, Yu-Xia Jiang, and Qian-Qian Zhang. 2014. “Spatiotemporal distribution and mass loadings of perfluoroalkyl substances in the Yangtze River of China.” Science of The Total Environment 493:580-587. https://doi.org/10.1016/j.scitotenv.2014.06.033.

Pan, Yitao, Yingshuang Zhu, Tongzhang Zheng, Qianqian Cui, Stephen L. Buka, Bin Zhang, Yong Guo, Wei Xia, Leo W. Y. Yeung, Yuanyuan Li, Aifen Zhou, Lin Qiu, Hongxiu Liu, Minmin Jiang, Chuansha Wu, Shunqing Xu, and Jiayin Dai. 2017. “Novel Chlorinated Polyfluorinated Ether Sulfonates and Legacy Per-/Polyfluoroalkyl Substances: Placental Transfer and Relationship with Serum Albumin and Glomerular Filtration Rate.” Environmental Science & Technology 51 (1):634-644. 10.1021/acs.est.6b04590.

Pan, Zihong, Xianling Yuan, Wenqing Tu, Zhengwei Fu, and Yuanxiang Jin. 2019. “Subchronic exposure of environmentally relevant concentrations of F-53B in mice resulted in gut barrier dysfunction and colonic inflammation in a sex-independent manner.” Environmental Pollution 253:268-277. https://doi.org/10.1016/j.envpol.2019.07.021.

Pannu, M., and Megan H. Plumlee. 2021. Orange County Water District: PFAS Phase I Pilot-Scale Treatment Study Final Report. Orange County Water District. https://www.ocwd.com/media/9829/2021-03-24_ocwd-pfas-pilot-i_finalreport.pdf.

Park, Hyunwoong, Chad D. Vecitis, Jie Cheng, Wonyong Choi, Brian T. Mader, and Michael R. Hoffmann. 2009. “Reductive Defluorination of Aqueous Perfluorinated Alkyl Surfactants: Effects of Ionic Headgroup and Chain Length.” The Journal of Physical Chemistry A 113 (4):690-696. 10.1021/jp807116q.

Park, H., C. D. Vecitis, J. Cheng, N. F. Dalleska, B. T. Mader, and M. R. Hoffmann. 2011. “Reductive degradation of perfluoroalkyl compounds with aquated electrons generated from iodide photolysis at 254 nm.” Photochem Photobiol Sci 10 (12):1945-53. 10.1039/c1pp05270e.

Park, S., C. de Perre, and L. S. Lee. 2017. “Alternate Reductants with VB12 to Transform C8 and C6 Perfluoroalkyl Sulfonates: Limitations and Insights into Isomer-Specific Transformation Rates, Products and Pathways.” Environ Sci Technol 51 (23):13869-13877. 10.1021/acs.est.7b03744.

Park, Saerom, Linda S. Lee, Victor F. Medina, Aaron Zull, and Scott Waisner. 2016. “Heat-activated persulfate oxidation of PFOA, 6:2 fluorotelomer sulfonate, and PFOS under conditions suitable for in-situ groundwater remediation.” Chemosphere 145:376-383. https://doi.org/10.1016/j.chemosphere.2015.11.097.

Parker, B. L., J. A. Cherry, and S. W. Chapman. 2004. “Field study of TCE diffusion profiles below DNAPL to assess aquitard integrity.” J Contam Hydrol 74 (1-4):197-230. 10.1016/j.jconhyd.2004.02.011.

Parsons, J. R., M. Saez, J. Dolfing, and P. de Voogt. 2008. “Biodegradation of perfluorinated compounds.” Rev Environ Contam Toxicol 196:53-71.

Patagonia. 2016. “An Update on Our DWR Problem.” Last Modified July 15, 2016. accessed 2021. https://www.patagonia.com/stories/our-dwr-problem-updated/story-17673.html.

Patlewicz, Grace, M. Richard Ann, J. Williams Antony, M. Grulke Christopher, Reeder Sams, Jason Lambert, D. Noyes Pamela, J. DeVito Michael, N. Hines Ronald, Mark Strynar, Annette Guiseppi-Elie, and S. Thomas Russell. “A Chemical Category-Based Prioritization Approach for Selecting 75 Per- and Polyfluoroalkyl Substances (PFAS) for Tiered Toxicity and Toxicokinetic Testing.” Environmental Health Perspectives 127 (1):014501. 10.1289/EHP4555.

Paul, Alexander G., Kevin C. Jones, and Andrew J. Sweetman. 2009. “A First Global Production, Emission, and Environmental Inventory for Perfluorooctane Sulfonate.” Environmental Science & Technology 43 (2):386-392. https://doi.org/10.1021/es802216n.

Payne, F.C., J.A. Quinnan, and S.T. Potter. 2008. Remediation Hydraulics: CRC Press. ISBN No. 9780849372490.

Peaslee, Graham F., John T. Wilkinson, Sean R. McGuinness, Meghanne Tighe, Nicholas Caterisano, Seryeong Lee, Alec Gonzales, Matthew Roddy, Simon Mills, and Krystle Mitchell. 2020. “Another Pathway for Firefighter Exposure to Per- and Polyfluoroalkyl Substances: Firefighter Textiles.” Environmental Science & Technology Letters 7 (8):594-599. 10.1021/acs.estlett.0c00410.

Pedone, L., D. Chillura Martino, E. Caponetti, M. A. Floriano, and R. Triolo. 1997. “Determination of the Composition of Mixed Hydrogenated and Fluorinated Micelles by Small Angle Neutron Scattering.” The Journal of Physical Chemistry B 101 (46):9525-9531. 10.1021/jp9722465.

PEER. 2019. Letter to Massachusetts Department of Environmental Protection Regarding Turf Field in Franklin, MA.

Pepper, Ian L., Mark L. Brusseau, Frank J. Prevatt, and Barbara A. Escobar. 2021. “Incidence of PFAS in soil following long-term application of class B biosolids.” Science of The Total Environment 793:148449. https://doi.org/10.1016/j.scitotenv.2021.148449.

Pereira, Luís A. M., Luís F. G. Martins, José R. Ascenso, Pedro Morgado, João P. Prates Ramalho, and Eduardo J. M. Filipe. 2014. “Diffusion Coefficients of Fluorinated Surfactants in Water: Experimental Results and Prediction by Computer Simulation.” Journal of Chemical & Engineering Data 59 (10):3151-3159. 10.1021/je500211w.

Pérez, Francisca, Martí Nadal, Alícia Navarro-Ortega, Francesc Fàbrega, José L. Domingo, Damià Barceló, and Marinella Farré. 2013. “Accumulation of perfluoroalkyl substances in human tissues.” Environment International 59:354-362. https://doi.org/10.1016/j.envint.2013.06.004.

Performance Fluoropolymer Partnership. 2021. “What are fluoropolymers?” accessed 2021. https://fluoropolymerpartnership.com.

Perkins, R. G., J. L. Butenhoff, G. L. Kennedy, Jr., and M. J. Palazzolo. 2004. “13-week dietary toxicity study of ammonium perfluorooctanoate (APFO) in male rats.” Drug Chem Toxicol 27 (4):361-78. 10.1081/DCT-200039773.

Persson, J., and N. Andersson. 2016. Modeling groundwater flow and PFOS transport. A case study at the old fire drill site of Bromma Stockholm Airport. Stockholm, Sweden. http://www.diva-portal.org/smash/get/diva2:946450/FULLTEXT02.pdf.

Peters, Jeffrey M., and Frank J. Gonzalez. 2011. “Why Toxic Equivalency Factors Are Not Suitable for Perfluoroalkyl Chemicals.” Chemical Research in Toxicology 24 (10):1601-1609. 10.1021/tx200316x.

Pétré, Marie-Amélie, David P. Genereux, Lydia Koropeckyj-Cox, Detlef R. U. Knappe, Sandrine Duboscq, Troy E. Gilmore, and Zachary R. Hopkins. 2021. “Per- and Polyfluoroalkyl Substance (PFAS) Transport from Groundwater to Streams near a PFAS Manufacturing Facility in North Carolina, USA.” Environmental Science & Technology 55 (9):5848-5856. 10.1021/acs.est.0c07978.

Phillips, S., P. Murphy, G. Brickle, and D. Burns. 2018. Validation of Foam Fractionation as an Effective Treatment Technology. OPEC Systems. https://www.opecsystems.com/persistent/catalogue_files/categories/opecsystemspfassolutionsposterforecoforum.pdf.

Pica, Nasim E., Joanna Funkhouser, Yiming Yin, Zuoyou Zhang, Donato M. Ceres, Tiezheng Tong, and Jens Blotevogel. 2019. “Electrochemical Oxidation of Hexafluoropropylene Oxide Dimer Acid (GenX): Mechanistic Insights and Efficient Treatment Train with Nanofiltration.” Environmental Science & Technology 53 (21):12602-12609. 10.1021/acs.est.9b03171.

Piekarz, Arkadiusz M., Toby Primbs, Jennifer A. Field, Douglas F. Barofsky, and Staci Simonich. 2007. “Semivolatile Fluorinated Organic Compounds in Asian and Western U.S. Air Masses.” Environmental Science & Technology 41 (24):8248-8255. 10.1021/es0713678.

Pietrzak, Damian. 2021. “Modeling migration of organic pollutants in groundwater — Review of available software.” Environmental Modelling & Software 144:105145. https://doi.org/10.1016/j.envsoft.2021.105145.

Pike, Kyndal A., Paul L. Edmiston, Jillian J. Morrison, and Jennifer A. Faust. 2021. “Correlation Analysis of Perfluoroalkyl Substances in Regional U.S. Precipitation Events.” Water Research 190:116685. https://doi.org/10.1016/j.watres.2020.116685.

Pillai, Suresh. 2016. Introduction to Electron-Beam Food Irradiation. Chemical Engineering Progress 112 (11): 36-44. https://www.aiche.org/resources/publications/cep/2016/november/introduction-electron-beam-food-irradiation.

Pillai, Suresh, and Shima Shayanfar. 2016. “Electron Beam Technology and Other Irradiation Technology Applications in the Food Industry.” Topics in Current Chemistry 375:6. https://doi.org/10.1007/s41061-016-0093-4.

Pinkard, Brian R., Conrad Austin, Anmol L. Purohit, Jianna Li, and Igor V. Novosselov. 2023. “Destruction of PFAS in AFFF-impacted fire training pit water, with a continuous hydrothermal alkaline treatment reactor.” Chemosphere 314:137681. https://doi.org/10.1016/j.chemosphere.2022.137681.

Place, Benjamin J., and Jennifer A. Field. 2012. “Identification of Novel Fluorochemicals in Aqueous Film-Forming Foams Used by the US Military.” Environmental Science & Technology 46 (13):7120-7127. 10.1021/es301465n.

Plain Language.gov. “Writing Effective Letters.” accessed 2020. https://www.plainlanguage.gov/resources/content-types/writing-effective-letters/.

Plastics Industry Association. 2019. Guide to the Safe Handling of Fluoropolymer Resins. Washington DC. https://access.plasticsindustry.org/ItemDetail?iProductCode=BU201&Category=PUBLICATIO&WebsiteKey=7cf6f8c9-ad49-40af-a01f-0b8c06a4b8f6.

Plumlee, Megan H., Kristopher McNeill, and Martin Reinhard. 2009. “Indirect Photolysis of Perfluorochemicals: Hydroxyl Radical-Initiated Oxidation of N-Ethyl Perfluorooctane Sulfonamido Acetate (N-EtFOSAA) and Other Perfluoroalkanesulfonamides.” Environmental Science & Technology 43 (10):3662-3668. 10.1021/es803411w.

Pohland, F.G., and J.T. Graven. 1993. The Use of Alternative Materials for Daily Cover at Municpal Solid Waste Landfills. EPA/600/SR-93/172: USEPA Research and Development.

Posner, Stefan, Sandra Roos, Pia Poulsen, Hrönn Jörundsdóttir, Gunlaugsdottir H, Xenia Trier, Allan Jensen, Athanasios Katsoyiannis, Dorte Herzke, Eva Cecilie Bonefeld-Jørgensen, Christina Jönsson, Gitte Alsing, Mandana Ghisari, and Sophie Jensen. 2013. Per- and polyfluorinated substances in the Nordic countries. Use, occurrence and toxicology. Copenhagen: Norden. ISBN No. 978-92-893-2562-2.

Post, G. B. 2013. Presentation Slides: Perfluorinated Chemicals (PFCs) – Emerging Drinking Water Contaminants. New Jersey Department of Environmental Protection Office of Science. http://www.state.nj.us/drbc/library/documents/TAC/06052013/toxics060513_post.pdf

Post, Gloria B. 2021. “Recent US State and Federal Drinking Water Guidelines for Per- and Polyfluoroalkyl Substances.” Environmental Toxicology and Chemistry 40 (3):550-563. https://doi.org/10.1002/etc.4863.

Post, Gloria B., Perry D. Cohn, and Keith R. Cooper. 2012. “Perfluorooctanoic acid (PFOA), an emerging drinking water contaminant: A critical review of recent literature.” Environmental Research 116:93-117. https://doi.org/10.1016/j.envres.2012.03.007.

Post, Gloria B., Jessie A. Gleason, and Keith R. Cooper. 2017. “Key scientific issues in developing drinking water guidelines for perfluoroalkyl acids: Contaminants of emerging concern.” PLOS Biology 15 (12):e2002855. https://doi.org/10.1371/journal.pbio.2002855.

Post, G. B., J. B. Louis, R. L. Lippincott, and N. A. Procopio. 2013. “Occurrence of perfluorinated compounds in raw water from New Jersey public drinking water systems.” Environmental Science & Technology 47 (23):13266-75. https://doi.org/10.1021/es402884x.

Poulsen, P. B., A. A. Jensen, E. Wallstrom, and E. N. P. R. O. Aps. 2005. More Environmentally Friendly Alternatives to PFOS-Compounds and PFOA. 1013: Danish Environmental Protection Agency Environmental Project.

Praveen, Chandni, Palmy R. Jesudhasan, Robert S. Reimers, and Suresh D. Pillai. 2013. “Electron beam inactivation of selected microbial pathogens and indicator organisms in aerobically and anaerobically digested sewage sludge.” Bioresource Technology 144:652-657. https://doi.org/10.1016/j.biortech.2013.07.034.

Preiss, F. 2022. Cleaning fire extinguishing systems that have been contaminated by fluorine foam agents. International Fire Fighter. https://iffmag.mdmpublishing.com/cleaning-fire-extinguishing-systems-that-have-been-contaminated-by-fluorine-foam-agents/.

Prell, C. 2011. Social Network Analysis: History, theory, methodology. London, United Kingdom: Sage Publications Ltd. ISBN No. 978-1412947152.

Prell, Christina, Klaus Hubacek, and Mark Reed. 2009. “Stakeholder Analysis and Social Network Analysis in Natural Resource Management.” Society & Natural Resources 22 (6):501-518. 10.1080/08941920802199202.

Presidential/Congressional Commission. 1997. Framework for Environmental Health Risk Management. Final Report. Volume 1. Washington, D.C.: The Presidential/Congressional Commission on Risk Assessment and Risk Management.

Prevedouros, Konstantinos, Ian T. Cousins, Robert C. Buck, and Stephen H. Korzeniowski. 2006. “Sources, Fate and Transport of Perfluorocarboxylates.” Environmental Science & Technology 40 (1):32-44. https://doi.org/10.1021/es0512475.

Princz, Juliska, Muriel Jatar, Heather Lemieux, and Rick Scroggins. 2018. “Perfluorooctane sulfonate in surface soils: Effects on reproduction in the collembolan, Folsomia candida, and the oribatid mite, Oppia nitens.” Chemosphere 208:757-763. https://doi.org/10.1016/j.chemosphere.2018.06.020.

Procopio, N. A., R. Karl, S. M. Goodrow, J. Maggio, J. B. Louis, and T. B. Atherholt. 2017. “Occurrence and source identification of perfluoroalkyl acids (PFAAs) in the Metedeconk River Watershed, New Jersey.” Environmental Science and Pollution Research 24:27125-27135. https://doi.org/10.1007/s11356-017-0309-3.

Psillakis, Elefteria, Jie Cheng, M. R. Hoffmann, and A. J. Colussi. 2009. “Additions/Corrections to Enrichment Factors of Perfluoroalkyl Oxoanions at the Air/Water Interface.” The Journal of Physical Chemistry A 113 (31):9050-9050. https://doi.org/10.1021/jp9058559.

Psillakis, Elefteria, Jie Cheng, M. R. Hoffmann, and A. J. Colussi. 2009. “Enrichment Factors of Perfluoroalkyl Oxoanions at the Air/Water Interface.” The Journal of Physical Chemistry A 113 (31):8826-8829. https://doi.org/10.1021/jp902795m.

Punyapalakul, Patiparn, Kuntida Suksomboon, Panida Prarat, and Sutha Khaodhiar. 2013. “Effects of Surface Functional Groups and Porous Structures on Adsorption and Recovery of Perfluorinated Compounds by Inorganic Porous Silicas.” Separation Science and Technology 48 (5):775-788. https://doi.org/10.1080/01496395.2012.710888.

Qanbarzadeh, Mojtaba, Laura DiGiacomo, Ehsan Bouteh, Eman Z. Alhamdan, Marc M. Mason, Bo Wang, Michael S. Wong, and Ezra L. Cates. 2023. “An Ultraviolet/Boron Nitride Photocatalytic Process Efficiently Degrades Poly-/Perfluoroalkyl Substances in Complex Water Matrices.” Environmental Science & Technology Letters 10 (8):705-710. 10.1021/acs.estlett.3c00363.

Qazi, M. R., M. R. Abedi, B. D. Nelson, J. W. DePierre, and M. Abedi-Valugerdi. 2010. “Dietary exposure to perfluorooctanoate or perfluorooctane sulfonate induces hypertrophy in centrilobular hepatocytes and alters the hepatic immune status in mice.” Int Immunopharmacol 10 (11):1420-7. 10.1016/j.intimp.2010.08.009.

Qi, Ping, Ying Wang, Jingli Mu, and Juying Wang. 2011. “Aquatic predicted no-effect-concentration derivation for perfluorooctane sulfonic acid.” Environmental Toxicology and Chemistry 30 (4):836-842. 10.1002/etc.460.

Qi, Yanjie, Zhuoshi He, Shouliang Huo, Jingtian Zhang, Beidou Xi, and Shibin Hu. 2017. “Source apportionment of perfluoroalkyl substances in surface sediments from lakes in Jiangsu Province, China: Comparison of three receptor models.” Journal of Environmental Sciences 57:321-328. https://doi.org/10.1016/j.jes.2016.12.007.

Qi, Yanjie, Shouliang Huo, Beidou Xi, Shibin Hu, Jingtian Zhang, and Zhuoshi He. 2016. “Spatial distribution and source apportionment of PFASs in surface sediments from five lake regions, China.” Scientific Reports 6:22674. https://doi.org/10.1038/srep22674.

Qu, Baocheng, Hongxia Zhao, and Jiti Zhou. 2010. “Toxic effects of perfluorooctane sulfonate (PFOS) on wheat (Triticum aestivum L.) plant.” Chemosphere 79 (5):555-560. https://doi.org/10.1016/j.chemosphere.2010.02.012.

Qu, Baocheng, Hongxia Zhao, and Jiti Zhou. 2010. “Toxic effects of perfluorooctane sulfonate (PFOS) on wheat (Triticum aestivum L.) plant.” Chemosphere 79 (5):555-560. https://doi.org/10.1016/j.chemosphere.2010.02.012.

Qu, Yan, Chaojie Zhang, Fei Li, Jing Chen, and Qi Zhou. 2010. “Photo-reductive defluorination of perfluorooctanoic acid in water.” Water Research 44 (9):2939-2947. https://doi.org/10.1016/j.watres.2010.02.019.

Qu, Yan, Chao-Jie Zhang, Pei Chen, Qi Zhou, and Wei-Xian Zhang. 2014. “Effect of initial solution pH on photo-induced reductive decomposition of perfluorooctanoic acid.” Chemosphere 107:218-223. https://doi.org/10.1016/j.chemosphere.2013.12.046.

Queensland Government. 2021. Operational Policy. Environmental Management of Fire Fighting Foam. Department of Environment and Science Queensland Government. https://www.qld.gov.au/__data/assets/pdf_file/0025/68470/firefighting-foam-policy.pdf.

Quinnan, J., P. Curry, M. Lupo, M. M. Miller, and M. Rossi. 2021. Validation of Streamlined Mobile Lab-Based Real Time PFAS Analytical Methods. Project ER19-5203: ESTCP. https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER19-5203.

Quinnan, Joseph, Michael Rossi, Patrick Curry, Mark Lupo, Margaret Miller, Helmer Korb, Cameron Orth, and Kristen Hasbrouck. 2021. “Application of PFAS-mobile lab to support adaptive characterization and flux-based conceptual site models at AFFF releases.” Remediation Journal 31 (3):7-26. https://doi.org/10.1002/rem.21680.

Quinnan, Joseph A., Colin Morrell, Nathan Nagle, and Ken G. Maynard. 2022. “Ex situ soil washing to remove PFAS adsorbed to soils from source zones.” Remediation Journal.

Quist, E. M., A. J. Filgo, C. A. Cummings, G. E. Kissling, M. J. Hoenerhoff, and S. E. Fenton. 2015. “Hepatic Mitochondrial Alteration in CD-1 Mice Associated with Prenatal Exposures to Low Doses of Perfluorooctanoic Acid (PFOA).” Toxicol Pathol 43 (4):546-57. 10.1177/0192623314551841.

Radford, M., L. Cook, M. Zamboni, J. Thorn, and J. Spalding. 2023. Determining the Presence of PFAS in Coated Bentonite Pellets. The Military Engineer. https://samenews.org/the-military-engineer/.

Radjenovic, Jelena, and David L. Sedlak. 2015. "Challenges and Opportunities for Electrochemical Processes as Next-Generation Technologies for the Treatment of Contaminated Water." Environmental Science & Technology 49 (19):11292-11302. 10.1021/acs.est.5b02414.

Radke Elizabeth, G., J. Michael Wright, Krista Christensen, J. Lin Cynthia, E. Goldstone Alexandra, Courtney Lemeris, and A. Thayer Kristina. 2022. "Epidemiology Evidence for Health Effects of 150 per- and Polyfluoroalkyl Substances: A Systematic Evidence Map." Environmental Health Perspectives 130 (9):096003. 10.1289/EHP11185.

Radolinski, Jesse, Hanh Le, Sheldon S. Hilaire, Kang Xia, Durelle Scott, and Ryan D. Stewart. 2022. "A spectrum of preferential flow alters solute mobility in soils." Scientific Reports 12 (1):4261. https://doi.org/10.1038/s41598-022-08241-w.

Rahman, Sheikh, Matthew Eckelman, Annalisa Onnis-Hayden, and April Gu. 2014. "Environmental Sustainability Assessment of Technologies for Removal of Contaminants of Emerging Concern." Proceedings of the Water Environment Federation 2014 (16):6455-6469. https://doi.org/10.2175/193864714815940785.

Raleigh, Katherine K., Bruce H. Alexander, Geary W. Olsen, Gurumurthy Ramachandran, Sandy Z. Morey, Timothy R. Church, Perry W. Logan, Laura L. F. Scott, and Elizabeth M. Allen. 2014. "Mortality and cancer incidence in ammonium perfluorooctanoate production workers." Occupational and Environmental Medicine 71 (7):500. 10.1136/oemed-2014-102109.

Ramhoj, L., U. Hass, J. Boberg, M. Scholze, S. Christiansen, F. Nielsen, and M. Axelstad. 2018. "Perfluorohexane Sulfonate (PFHxS) and a Mixture of Endocrine Disrupters Reduce Thyroxine Levels and Cause Antiandrogenic Effects in Rats." Toxicol Sci 163 (2):579-591. 10.1093/toxsci/kfy055.

Rand, Amy, John Rooney, Craig Butt, Joel N. Meyer, and Scott A. Mabury. 2013. "Cellular Toxicity Associated with Exposure to Perfluorinated Carboxylates (PFCAs) and Their Metabolic Precursors." Chemical Research in Toxicology 27 (1):42-50. https://doi.org/10.1021/tx400317p.

Rand, Amy A., and Scott A. Mabury. 2016. "Is there a human health risk associated with indirect exposure to perfluorinated carboxylates (PFCAs)?" Toxicology 375:28-36. https://doi.org/10.1016/j.tox.2016.11.011.

Rankin, Keegan, Holly Lee, Pablo J. Tseng, and Scott A. Mabury. 2014. "Investigating the Biodegradability of a Fluorotelomer-Based Acrylate Polymer in a Soil–Plant Microcosm by Indirect and Direct Analysis." Environmental Science & Technology 48 (21):12783-12790. 10.1021/es502986w.

Rankin, Keegan, and Scott A. Mabury. 2015. "Matrix Normalized MALDI-TOF Quantification of a Fluorotelomer-Based Acrylate Polymer." Environmental Science & Technology 49 (10):6093-6101. 10.1021/es505931v.

Rankin, Keegan, Scott A. Mabury, Thomas M. Jenkins, and John W. Washington. 2016. "A North American and global survey of perfluoroalkyl substances in surface soils: Distribution patterns and mode of occurrence." Chemosphere 161:333-341. https://doi.org/10.1016/j.chemosphere.2016.06.109.

Rao, N. S., and B. E. Baker. 1994. "Textile Finishes and Fluorosurfactants." In Organofluorine Chemistry. Topics in Applied Chemistry, edited by R.E. Banks, B.E. Smart and J.C. Tatlow, 321-338. Boston, MA: Springer. ISBN No. 978-1-4899-1204-6.

Rappazzo, K. M., E. Coffman, and E. P. Hines. 2017. "Exposure to Perfluorinated Alkyl Substances and Health Outcomes in Children: A Systematic Review of the Epidemiologic Literature." Int J Environ Res Public Health 14 (7). 10.3390/ijerph14070691.

Ras, C., and Harro von Blottnitz. 2012. "A comparative life cycle assessment of process water treatment technologies at the Secunda industrial complex, South Africa." Water SA 38 (4):549-554. https://doi.org/10.4314/wsa.v38i4.10.

Raschke, Anna, A. Pouyan Nejadhashemi, Vahid Rafiei, Nicolas Fernandez, Afshin Shabani, and Shu-Guang Li. 2022. "Opportunities and Challenges of Integrated Large-Scale PFAS Modeling: A Case Study for PFAS Modeling at a Watershed Scale." Journal of Environmental Engineering 148 (9):05022005.

doi:10.1061/(ASCE)EE.1943-7870.0002034.

Rattanaoudom, R., Chettiyappan Visvanathan, and S. K. Boontanon. 2012. "Removal of concentrated PFOS and PFOA in synthetic industrial wastewater by powder activated carbon and hydrotalcite." Journal of Water Sustainability 2:245-258.

Rauert, Cassandra, Tom Harner, Jasmin K. Schuster, Anita Eng, Gilberto Fillmann, Luisa Eugenia Castillo, Oscar Fentanes, Martín Villa Ibarra, Karina S. B. Miglioranza, Isabel Moreno Rivadeneira, Karla Pozo, and Beatriz Helena Aristizábal Zuluaga. 2018. "Atmospheric Concentrations of New Persistent Organic Pollutants and Emerging Chemicals of Concern in the Group of Latin America and Caribbean (GRULAC) Region." Environmental Science & Technology 52 (13):7240-7249. 10.1021/acs.est.8b00995.

Rauert, Cassandra, Mahiba Shoieb, Jasmin K. Schuster, Anita Eng, and Tom Harner. 2018. "Atmospheric concentrations and trends of poly- and perfluoroalkyl substances (PFAS) and volatile methyl siloxanes (VMS) over 7 years of sampling in the Global Atmospheric Passive Sampling (GAPS) network." Environmental Pollution 238:94-102. https://doi.org/10.1016/j.envpol.2018.03.017.

Rayaroth, Manoj, Usha Aravind, and Charuvila Aravindakumar. 2016. "Degradation of pharmaceuticals by ultrasound-based advanced oxidation process." Environmental Chemistry Letters 14:259-290. https://doi.org/10.1007/s10311-016-0568-0.

Rayne, S., and K. Forest. 2009. "Perfluoroalkyl sulfonic and carboxylic acids: a critical review of physicochemical properties, levels and patterns in waters and wastewaters, and treatment methods." J Environ Sci Health A Tox Hazard Subst Environ Eng 44 (12):1145-99. 10.1080/10934520903139811.

Rayne, S., K. Forest, and K. J. Friesen. 2008. "Congener-specific numbering systems for the environmentally relevant C4 through C8 perfluorinated homologue groups of alkyl sulfonates, carboxylates, telomer alcohols, olefins, and acids, and their derivatives." J Environ Sci Health A Tox Hazard Subst Environ Eng 43 (12):1391-401. 10.1080/10934520802232030.

Rebholz, Sandra L., Thomas Jones, Robert L. Herrick, Changchun Xie, Antonia M. Calafat, Susan M. Pinney, and Laura A. Woollett. 2016. "Hypercholesterolemia with consumption of PFOA-laced Western diets is dependent on strain and sex of mice." Toxicology Reports 3:46-54. https://doi.org/10.1016/j.toxrep.2015.11.004.

Reed, M. S., A. Graves, N. Dandy, H. Posthumus, K. Hubacek, J. Morris, C. Prell, C. H. Quinn, and L. C. Stringer. 2009. "'Who's in and why?' A typology of stakeholder analysis methods for natural resource management." Journal of Environmental Management 90 (5):1933-49.

Regenesis. 2019. "Webinar: PFAS Contamination in Minnesota, Lessons Learned, Fate and Transport, and Reducing Exposure. Ginny Yingling, MN Dept of Health." http://www2.regenesis.com/ginny-yingling.

Regenesis. 2020. Case Study: Michigan Dept. of Military and Veteran Affairs Employs PlumeStop at Grayling Army Airfield. https://regenesis.com/wp-content/uploads/2019/02/REGENESIS_Camp_Grayling_2020_10_19_01.pdf.

Reiner, Jessica L., Steven G. O'Connell, Amanda J. Moors, John R. Kucklick, Paul R. Becker, and Jennifer M. Keller. 2011. "Spatial and Temporal Trends of Perfluorinated Compounds in Beluga Whales (Delphinapterus leucas) from Alaska." Environmental Science & Technology 45 (19):8129-8136. 10.1021/es103560q.

Reiner, J. L., and Benjamin J. Place. 2015. "Perfluorinated Alkyl Acids in Wildlife." In Toxicological Effects of Perfluoroalkyl and Polyfluoralkyl Substances., edited by J.C. DeWitt. Humana Press, Cham. ISBN No. 978-3-319-15517-3.

Renner, Rebecca. 2001. "Growing Concern Over Perfluorinated Chemicals." Environmental Science & Technology 35 (7):154A-160A. 10.1021/es012317k.

Research Toxicology Centre. 2005. 4-week oral toxicity study in rats followed by 2-week recovery period. RTC Study No. 27080. https://www.nj.gov/dep/dsr/4-week-oral-toxicity-study-in-rats-2005.pdf.

Research Toxicology Centre. 2006. 4-week oral toxicity study in rats, followed by a 2-week recovery period. CAS # 330809-92-2. Volumes I and II. RTC Study No. 36710. https://www.nj.gov/dep/dsr/4-week-oral-toxicity-study-in-rats-2006.pdf.

Research Toxicology Centre. 2006. 13-week oral toxicity study in rats followed by an 8-week recovery period. RTC Study No. 41950. https://www.nj.gov/dep/dsr/13-week-oral-toxicity-study-in-rats-2006.pdf.

Research Toxicology Centre. 2016. 13-week oral toxicity study in rats followed by a 8-week recovery period. CAS # 330809-92-2. Audited draft report. RTC Study No. A1474. https://www.nj.gov/dep/dsr/13-week-oral-toxicity-study-in-rats-2016.pdf.

Rhoads, Kurt R., Elisabeth M. L. Janssen, Richard G. Luthy, and Craig S. Criddle. 2008. “Aerobic Biotransformation and Fate of N-Ethyl Perfluorooctane Sulfonamidoethanol (N-EtFOSE) in Activated Sludge.” Environmental Science & Technology 42 (8):2873-2878. 10.1021/es702866c.

Rhoads, Kurt R., Katherine H. Rostkowski, Peter K. Kitanidis, and Craig S. Criddle. 2013. “Use of on-site bioreactors to estimate the biotransformation rate of N-ethyl perfluorooctane sulfonamidoethanol (N-EtFOSE) during activated sludge treatment.” Chemosphere 92 (6):702-707. https://doi.org/10.1016/j.chemosphere.2013.04.059.

Rice, Penelope A., Jason Aungst, Jessica Cooper, Omari Bandele, and Shruti V. Kabadi. 2020. “Comparative analysis of the toxicological databases for 6:2 fluorotelomer alcohol (6:2 FTOH) and perfluorohexanoic acid (PFHxA).” Food and Chemical Toxicology 138:111210. https://doi.org/10.1016/j.fct.2020.111210.

Rich, Courtney D., Andrea C. Blaine, Lakhwinder Hundal, and Christopher P. Higgins. 2015. “Bioaccumulation of Perfluoroalkyl Acids by Earthworms (Eisenia fetida) Exposed to Contaminated Soils.” Environmental Science & Technology 49 (2):881-888. https://doi.org/10.1021/es504152d.

Richard, Ann M., Hannah Hidle, Grace Patlewicz, and Antony J. Williams. 2022. “Identification of Branched and Linear Forms of PFOA and Potential Precursors: A User-Friendly SMILES Structure-based Approach.” Frontiers in Environmental Science 10.

Richard, Ann M., Ryan Lougee, Matthew Adams, Hannah Hidle, Chihae Yang, James Rathman, Tomasz Magdziarz, Bruno Bienfait, Antony J. Williams, and Grace Patlewicz. 2023. “A New CSRML Structure-Based Fingerprint Method for Profiling and Categorizing Per- and Polyfluoroalkyl Substances (PFAS).” Chemical Research in Toxicology. 10.1021/acs.chemrestox.2c00403.

Richter, Lauren, Alissa Cordner, and Phil Brown. 2018. “Non-stick science: Sixty years of research and (in)action on fluorinated compounds.” Social Studies of Science 48 (5):691-714. https://doi.org/10.1177/0306312718799960.

Riddell, Nicole, Gilles Arsenault, Jonathan P. Benskin, Brock Chittim, Jonathan W. Martin, Alan McAlees, and Robert McCrindle. 2009. “Branched Perfluorooctane Sulfonate Isomer Quantification and Characterization in Blood Serum Samples by HPLC/ESI-MS(/MS).” Environmental Science & Technology 43 (20):7902-7908. 10.1021/es901261v.

Riedel, Theran P., Johnsie R. Lang, Mark J. Strynar, Andrew B. Lindstrom, and John H. Offenberg. 2019. “Gas-Phase Detection of Fluorotelomer Alcohols and Other Oxygenated Per- and Polyfluoroalkyl Substances by Chemical Ionization Mass Spectrometry.” Environmental Science & Technology Letters 6 (5):289-293. 10.1021/acs.estlett.9b00196.

Riedel, Theran P., M. Ariel Geer Wallace, Erin P. Shields, Jeffrey V. Ryan, Chun Wai Lee, and William P. Linak. 2021. “Low temperature thermal treatment of gas-phase fluorotelomer alcohols by calcium oxide.” Chemosphere 272:129859. https://doi.org/10.1016/j.chemosphere.2021.129859.

Ritscher, A., Z. Wang, M. Scheringer, J. M. Boucher, L. Ahrens, U. Berger, S. Bintein, S. K. Bopp, D. Borg, A. M. Buser, I. Cousins, J. DeWitt, T. Fletcher, C. Green, D. Herzke, C. Higgins, J. Huang, H. Hung, T. Knepper, C. S. Lau, E. Leinala, A. B. Lindstrom, J. Liu, M. Miller, K. Ohno, N. Perkola, Y. Shi, L. Småstuen Haug, X. Trier, S. Valsecchi, K. van der Jagt, and L. Vierke. 2018. “Zürich Statement on Future Actions on Per- and Polyfluoroalkyl Substances (PFASs).” Environ Health Perspect 126 (8):84502. 10.1289/ehp4158.

Ritter, Evelyn E., Margaret E. Dickinson, John P. Harron, David M. Lunderberg, Paul A. DeYoung, Alix E. Robel, Jennifer A. Field, and Graham F. Peaslee. 2017. “PIGE as a screening tool for Per- and polyfluorinated substances in papers and textiles.” Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 407:47-54. https://doi.org/10.1016/j.nimb.2017.05.052.

RIVM. 2016. Evaluation of substances used in the GenX technology by Chemours, Dordrecht. RIVM Letter Report

2016-0174. The Netherlands: RIVM. https://www.rivm.nl/en/about-rivm/corporate-publications/annual-report/scientific-report-rivm.

Robel, Alix E., Kristin Marshall, Margaret Dickinson, David Lunderberg, Craig Butt, Graham Peaslee, Heather M. Stapleton, and Jennifer A. Field. 2017. “Closing the Mass Balance on Fluorine on Papers and Textiles.” Environmental Science & Technology 51 (16):9022-9032. 10.1021/acs.est.7b02080.

Robertson, J. C. 1986. Potential for environmental impact of AFA-6 surfactant. EPA Docket AR266-1030a043. Missassauga, Ontario, Canada: Beak Consultants Ltd.

Robey, Nicole M., Bianca F. da Silva, Michael D. Annable, Timothy G. Townsend, and John A. Bowden. 2020. “Concentrating Per- and Polyfluoroalkyl Substances (PFAS) in Municipal Solid Waste Landfill Leachate Using Foam Separation.” Environmental Science & Technology 54 (19):12550-12559. 10.1021/acs.est.0c01266.

Rodowa, Alix E., Emerson Christie, Jane Sedlak, Graham F. Peaslee, Dorin Bogdan, Bill DiGuiseppi, and Jennifer A. Field. 2020. “Field Sampling Materials Unlikely Source of Contamination for Perfluoroalkyl and Polyfluoroalkyl Substances in Field Samples.” Environmental Science & Technology Letters 7 (3):156-163. https://doi.org/10.1021/acs.estlett.0c00036.

Rodriguez, Kelsey L., Jae-Hoon Hwang, Amirsalar R. Esfahani, A. H. Sadmani, and Woo H. Lee. 2020. “Recent Developments of PFAS-Detecting Sensors and Future Direction: A Review.” Micromachines 11 (7). http://doi.org/10.3390/mi11070667.

Rodriguez-Freire, Lucia, Rajesh Balachandran, Reyes Sierra-Alvarez, and Manish Keswani. 2015. “Effect of sound frequency and initial concentration on the sonochemical degradation of perfluorooctane sulfonate (PFOS).” Journal of Hazardous Materials 300:662-669. https://doi.org/10.1016/j.jhazmat.2015.07.077.

Rogers, J. M., R. G. Ellis-Hutchings, B. E. Grey, R. M. Zucker, J. Norwood, Jr., C. E. Grace, C. J. Gordon, and C. Lau. 2014. “Elevated blood pressure in offspring of rats exposed to diverse chemicals during pregnancy.” Toxicol Sci 137 (2):436-46. 10.1093/toxsci/kft248.

Rolland, Jason P., R. Michael Van Dam, Derek A. Schorzman, Stephen R. Quake, and Joseph M. DeSimone. 2004. “Solvent-Resistant Photocurable “Liquid Teflon” for Microfluidic Device Fabrication.” Journal of the American Chemical Society 126 (8):2322-2323. 10.1021/ja031657y.

Roostaei, Javad, Sarah Colley, Riley Mulhern, Andrew A. May, and Jacqueline MacDonald Gibson. 2021. “Predicting the risk of GenX contamination in private well water using a machine-learned Bayesian network model.” Journal of Hazardous Materials 411:125075. https://doi.org/10.1016/j.jhazmat.2021.125075.

Rosansky, Stephen. 2021. “Applying Supercritical Water Oxidation to Destroy PFAS.” The Military Engineer 113. https://samenews.org/applying-supercritical-water-oxidation-to-destroy-pfas/.

Ross, I., E. Houtz, J. McDonough, and P. Storch. 2019. “Full-Scale Treatment of PFAS-Impacted Wastewater Using Ozofractionation with Treatment Validation Using TOP Assay.” Battelle Sediments Conference, New Orleans, LA, February 11-14, 2019 https://www.battelle.org/docs/default-source/conferences/sediments-conference/proceedings/2019-sediments-conference-proceedings/a7.-characterization-and-remediation-of-pfas-contaminated-sediments-media/532.pdf?sfvrsn=75dc9522_2.

Ross, Ian, Jeffrey McDonough, Jonathan Miles, Peter Storch, Parvathy Thelakkat Kochunarayanan, Erica Kalve, Jake Hurst, Soumitri S. Dasgupta, and Jeff Burdick. 2018. “A review of emerging technologies for remediation of PFASs.” Remediation Journal 28 (2):101-126. 10.1002/rem.21553.

Rotander, A., L. M. Toms, L. Aylward, M. Kay, and J. F. Mueller. 2015. “Elevated levels of PFOS and PFHxS in firefighters exposed to aqueous film forming foam (AFFF).” Environ Int 82:28-34. 10.1016/j.envint.2015.05.005.

Roth, Julia, Ibrahim Abusallout, Tiffany Hill, Chase Holton, Utsav Thapa, and David Hanigan. 2020. “Release of Volatile Per- and Polyfluoroalkyl Substances from Aqueous Film-Forming Foam.” Environmental Science & Technology Letters 7 (3):164-170. https://doi.org/10.1021/acs.estlett.0c00052.

Roth, Julia, Ibrahim Abusallout, Tiffany Hill, Chase Holton, Utsav Thapa, and David Hanigan. 2020. “Response to Comment on “Release of Volatile Per- and Polyfluoroalkyl Substances from Aqueous Film-Forming Foam”.” Environmental Science & Technology Letters 7 (11):869-870. https://doi.org/10.1021/acs.estlett.0c00678.

Roth, K., Z. Yang, M. Agarwal, W. Liu, Z. Peng, Z. Long, J. Birbeck, J. Westrick, W. Liu, and M. C. Petriello. 2021. “Exposure to a mixture of legacy, alternative, and replacement per- and polyfluoroalkyl substances (PFAS) results in sex-dependent modulation of cholesterol metabolism and liver injury.” Environ Int 157:106843. 10.1016/j.envint.2021.106843.

Routti, Heli, Jon Aars, Eva Fuglei, Linda Hanssen, Karen Lone, Anuschka Polder, Åshild Ø Pedersen, Sabrina Tartu, Jeffrey M. Welker, and Nigel G. Yoccoz. 2017. “Emission Changes Dwarf the Influence of Feeding Habits on Temporal Trends of Per- and Polyfluoroalkyl Substances in Two Arctic Top Predators.” Environmental Science & Technology 51 (20):11996-12006. 10.1021/acs.est.7b03585.

Roux, I. le, H. M. Krieg, C. A. Yeates, and J. C. Breytenbach. 2005. “Use of chitosan as an antifouling agent in a membrane bioreactor.” Journal of Membrane Science 248 (1):127-136. https://doi.org/10.1016/j.memsci.2004.10.005.

Rovero, Matt, Diana Cutt, Rachel Griffiths, Urszula Filipowicz, Katherine Mishkin, Brad White, Sandra Goodrow, and Richard T. Wilkin. 2021. “Limitations of Current Approaches for Predicting Groundwater Vulnerability from PFAS Contamination in the Vadose Zone.” Groundwater Monitoring & Remediation n/a (n/a). https://doi.org/10.1111/gwmr.12485.

Royal Society of Chemistry. 2021. Policy Position: Risk-based regulation for per- and poly-fluoroalkyl substances (PFAS). https://www.rsc.org/globalassets/22-new-perspectives/sustainability/a-chemicals-strategy-for-a-sustainable-chemicals-revolution/pfas-policy-position-dec-2021.pdf.

Royer, Laurel A., Linda S. Lee, Mark H. Russell, Loring F. Nies, and Ronald F. Turco. 2015. “Microbial transformation of 8:2 fluorotelomer acrylate and methacrylate in aerobic soils.” Chemosphere 129:54-61. https://doi.org/10.1016/j.chemosphere.2014.09.077.

RPA. 2004. Perfluorooctane Sulphonate – Risk reduction strategy and analysis of advantages and drawbacks. Loddon, UK: Food and Rural Affairs and the Environment Agency for England and Wales Department for Environment. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/183154/pfos-riskstrategy.pdf.

Ruan, Ting, Yongfeng Lin, Thanh Wang, Guibin Jiang, and Ning Wang. 2015. “Methodology for studying biotransformation of polyfluoroalkyl precursors in the environment.” TrAC Trends in Analytical Chemistry 67:167-178. https://doi.org/10.1016/j.trac.2014.11.017.

Ruan, Ting, Bogdan Szostek, Patrick W. Folsom, Barry W. Wolstenholme, Runzeng Liu, Jiyan Liu, Guibin Jiang, Ning Wang, and Robert C. Buck. 2013. “Aerobic Soil Biotransformation of 6:2 Fluorotelomer Iodide.” Environmental Science & Technology 47 (20):11504-11511. https://doi.org/10.1021/es4018128.

Rusch, G.M. 1979. An Acute Inhalation Study of T-2305 CoC in the Rat. Study No. 78-7184. (Cited in USEPA, 2016 – 822-R-16-003).

Rusch, G.M., W.E. Rinehart, and C.A. Bozak. 1979. An Acute Inhalation Toxicity Study of T-2306 CoC in the Rat. Project No. 78-7185 (Cited in USEPA, 2016 – EPA 822-R-16-002): Bio/dynamics Inc.

Rushing, B., Q. Hu, J. Franklin, R. McMahen, S. Dagnio, C. Higgins, M. Strynar, and J. DeWitt. 2017. “Evaluation of the Immunomodulatory Effects of 2,3,3,3-Tetrafluoro-2-(Heptafluoropropoxy)- Propanoate in C57BL/6 Mice.” Toxicol Sci 156:179-189. 10.1093/toxsci/kfw25.

Russell, Mark H., William R. Berti, Bogdan Szostek, and Robert C. Buck. 2008. “Investigation of the Biodegradation Potential of a Fluoroacrylate Polymer Product in Aerobic Soils.” Environmental Science & Technology 42 (3):800-807. 10.1021/es0710499.

Russell, Mark H., William R. Berti, Bogdan Szostek, Ning Wang, and Robert C. Buck. 2010. “Evaluation of PFO formation from the biodegradation of a fluorotelomer-based urethane polymer product in aerobic soils.” Polymer Degradation and Stability 95 (1):79-85. https://doi.org/10.1016/j.polymdegradstab.2009.10.004.

Russell, Mark H., Matthew W. Himmelstein, and Robert C. Buck. 2015. "Inhalation and oral toxicokinetics of 6:2 FTOH and its metabolites in mammals." Chemosphere 120:328-335. https://doi.org/10.1016/j.chemosphere.2014.07.092.

Russell, M. H., H. Nilsson, and R. C. Buck. 2013. "Elimination kinetics of perfluorohexanoic acid in humans and comparison with mouse, rat and monkey." Chemosphere 93 (10):2419-25. 10.1016/j.chemosphere.2013.08.060.

Ruyle, Bridger J., Colin P. Thackray, James P. McCord, Mark J. Strynar, Kevin A. Mauge-Lewis, Suzanne E. Fenton, and Elsie M. Sunderland. 2021. "Reconstructing the Composition of Per- and Polyfluoroalkyl Substances in Contemporary Aqueous Film-Forming Foams." Environmental Science & Technology Letters 8 (1):59-65. 10.1021/acs.estlett.0c00798.

RWQCB-CVR. 2016. Water Quality Control Plan (Basin Plan) for the California Regional Water Quality Control Board, Central Valley Region, Fourth Edition, Sacramento and San Joaquin River Basins.

SA EPA. 2017. Consultation Report: Draft amendment to ban the use of fire-fighting foams containing perfluorinated alkylated substances (PFAS). Adelaide, SA: South Australia Environment Protection Authority. www.epa.sa.gov.au.

SA EPA. 2019. Transitioning to Fluorine-Free Firefighting Foam, Water Quality Information Sheet. https://www.epa.sa.gov.au/files/14237_info_fluorine_free_pfas.pdf.

Sacramento State University. 2019. "Empty Bed Contact Time Definition." Office of Water Programs, Department of Civil Engineering, Accessed 01-25-2020. https://www.owp.csus.edu/glossary/empty-bed-contact-time.php.

Saez, M., P. de Voogt, and J. R. Parsons. 2008. "Persistence of perfluoroalkylated substances in closed bottle tests with municipal sewage sludge." Environ Sci Pollut Res Int 15 (6):472-7. 10.1007/s11356-008-0020-5.

Saito, N., K. Harada, K. Inoue, K. Sasaki, T. Yoshinaga, and A. Koizumi. 2004. "Perfluorooctanoate and perfluorooctane sulfonate concentrations in surface water in Japan." J Occup Health 46 (1):49-59. 10.1539/joh.46.49.

Salice, Christopher J., Todd A. Anderson, Richard H. Anderson, and Adric D. Olson. 2018. "Ecological risk assessment of perfluooroctane sulfonate to aquatic fauna from a bayou adjacent to former fire training areas at a US Air Force installation." Environmental Toxicology and Chemistry 37 (8):2198-2209. https://doi.org/10.1002/etc.4162.

Salvatore, Derrick, Kira Mok, Kimberly K. Garrett, Grace Poudrier, Phil Brown, Linda S. Birnbaum, Gretta Goldenman, Mark F. Miller, Sharyle Patton, Maddy Poehlein, Julia Varshavsky, and Alissa Cordner. 2022. "Presumptive Contamination: A New Approach to PFAS Contamination Based on Likely Sources." Environmental Science & Technology Letters 9 (11):983-990. https://doi.org/10.1021/acs.estlett.2c00502.

Sandman, P. 2013. Responding to Community Outrage: Strategies for Effective Risk Communication. American Industrial Hygiene Association.

Sant, Karilyn E., Olivia L. Venezia, Paul P. Sinno, and Alicia R. Timme-Laragy. 2018. "Perfluorobutanesulfonic Acid Disrupts Pancreatic Organogenesis and Regulation of Lipid Metabolism in the Zebrafish, Danio rerio." Toxicological Sciences 167 (1):258-268. 10.1093/toxsci/kfy237.

Santangelo, L.M., A.K. Tokranov, S.M. Welch, K.E.A. Schlosser, J.M. Marts, A.F. Drouin, J.D. Ayotte, A.E. Rousseau, and J.L. Harfmann. 2022. Statewide survey of shallow soil concentrations of per- and polyfluoroalkyl substances (PFAS) and related chemical and physical data across New Hampshire, 2021. U.S. Geological Survey data release. https://doi.org/10.5066/P9KG38B5.

Sasi, Pavankumar Challa, Ali Alinezhad, Bin Yao, Alena Kubátová, Svetlana A. Golovko, Mikhail Y. Golovko, and Feng Xiao. 2021. "Effect of granular activated carbon and other porous materials on thermal decomposition of per- and polyfluoroalkyl substances: Mechanisms and implications for water purification." Water Research 200:117271. https://doi.org/10.1016/j.watres.2021.117271.

Sato, I., K. Kawamoto, Y. Nishikawa, S. Tsuda, M. Yoshida, K. Yaegashi, N. Saito, W. Liu, and Y. Jin. 2009. "Neurotoxicity of perfluorooctane sulfonate (PFOS) in rats and mice after single oral exposure." J Toxicol Sci 34 (5):569-74.

Savitz, D. A., C. R. Stein, S. M. Bartell, B. Elston, J. Gong, H. M. Shin, and G. A. Wellenius. 2012. "Perfluorooctanoic acid exposure and pregnancy outcome in a highly exposed community." Epidemiology 23 (3):386-92. 10.1097/EDE.0b013e31824cb93b.

Savvaides, Tina, Jeremy P. Koelmel, Yakun Zhou, Elizabeth Z. Lin, Paul Stelben, Juan J. Aristizabal-Henao, John A. Bowden, and Krystal J. Godri Pollitt. 2021. "Prevalence and Implications of Per- and Polyfluoroalkyl Substances (PFAS) in Settled Dust." Current Environmental Health Reports 8 (4):323-335. 10.1007/s40572-021-00326-4.

Schaefer, Charles, E., Dung Nguyen, Emerson Christie, Stefanie Shea, P. Higgins Christopher, and A. Field Jennifer. 2021. "Desorption of Poly- and Perfluoroalkyl Substances from Soil Historically Impacted with Aqueous Film-Forming Foam." Journal of Environmental Engineering 147 (2):06020006. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001846.

Schaefer, C. E. 2018. "Electrochemical Treatment of AFFF-Impacted Groundwater." Emerging Contaminants Summit, Westminster, Colorado, March 6-7, 2018.

Schaefer, Charles E., Christina Andaya, Aniela Burant, Charles W. Condee, Ana Urtiaga, Timothy J. Strathmann, and Christopher P. Higgins. 2017. "Electrochemical treatment of perfluorooctanoic acid and perfluorooctane sulfonate: Insights into mechanisms and application to groundwater treatment." Chemical Engineering Journal 317:424-432. https://doi.org/10.1016/j.cej.2017.02.107.

Schaefer, Charles E., Christina Andaya, Ana Urtiaga, Erica R. McKenzie, and Christopher P. Higgins. 2015. "Electrochemical treatment of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) in groundwater impacted by aqueous film forming foams (AFFFs)." Journal of Hazardous Materials 295:170-175. https://doi.org/10.1016/j.jhazmat.2015.04.024.

Schaefer, Charles E., Sarah Choyke, P. Lee Ferguson, Christina Andaya, Aniela Burant, Andrew Maizel, Timothy J. Strathmann, and Christopher P. Higgins. 2018. "Electrochemical Transformations of Perfluoroalkyl Acid (PFAA) Precursors and PFAAs in Groundwater Impacted with Aqueous Film Forming Foams." Environmental Science & Technology 52 (18):10689-10697. 10.1021/acs.est.8b02726.

Schaefer, Charles E., Veronika Culina, Dung Nguyen, and Jennifer Field. 2019. "Uptake of Poly- and Perfluoroalkyl Substances at the Air–Water Interface." Environmental Science & Technology 53 (21):12442-12448. https://doi.org/10.1021/acs.est.9b04008.

Schaefer, Charles E., Jennifer Hooper, Mahsa Modiri-Gharehveran, Dina M. Drennan, Ned Beecher, and Linda Lee. 2022. "Release of poly- and perfluoroalkyl substances from finished biosolids in soil mesocosms." Water Research 217:118405. https://doi.org/10.1016/j.watres.2022.118405.

Schaefer, Charles E., Jennifer L. Hooper, Laurel E. Strom, Ibrahim Abusallout, Eric R. V. Dickenson, Kyle A. Thompson, Gayathri Ram Mohan, Dina Drennan, Ke Wu, and Jennifer L. Guelfo. 2023. "Occurrence of quantifiable and semi-quantifiable poly- and perfluoroalkyl substances in united states wastewater treatment plants." Water Research 233:119724. https://doi.org/10.1016/j.watres.2023.119724.

Schaefer, Charles E., Graig M. Lavorgna, David R. Lippincott, Dung Nguyen, Emerson Christie, Stefanie Shea, Sean O'Hare, Maria C. S. Lemes, Christopher P. Higgins, and Jennifer Field. 2022. "A field study to assess the role of air-water interfacial sorption on PFAS leaching in an AFFF source area." Journal of Contaminant Hydrology 248:104001. https://doi.org/10.1016/j.jconhyd.2022.104001.

Schaefer Charles, E., Christina Andaya, Andrew Maizel, and P. Higgins Christopher. 2019. "Assessing Continued Electrochemical Treatment of Groundwater Impacted by Aqueous Film-Forming Foams." Journal of Environmental Engineering 145 (12):06019007. 10.1061/(ASCE)EE.1943-7870.0001605.

Schaider, L. A., J. M. Ackerman, and R. A. Rudel. 2016. "Septic systems as sources of organic wastewater compounds in domestic drinking water wells in a shallow sand and gravel aquifer." Sci Total Environ 547:470-481. 10.1016/j.scitotenv.2015.12.081.

Schaider, Laurel A., Simona A. Balan, Arlene Blum, David Q. Andrews, Mark J. Strynar, Margaret E. Dickinson, David M. Lunderberg, Johnsie R. Lang, and Graham F. Peaslee. 2017. "Fluorinated Compounds in U.S. Fast Food Packaging." Environmental Science & Technology Letters 4 (3):105-111. https://doi.org/10.1021/acs.estlett.6b00435.

Scheitlin, Christopher G., Kavitha Dasu, Stephen Rosansky, Lindy Espina Dejarme, Dinusha Siriwardena, Jonathan Thorn, Larry Mullins, Ian Haggerty, Krenar Shqau, and Julia Stowe. 2023. “Application of Supercritical Water Oxidation to Effectively Destroy Per- and Polyfluoroalkyl Substances in Aqueous Matrices.” ACS ES&T Water. 10.1021/acsestwater.2c00548.

Schellenberger, Steffen, Christina Jönsson, Pelle Mellin, Oscar A. Levenstam, Ioannis Liagkouridis, Anton Ribbenstedt, Anne-Charlotte Hanning, Lara Schultes, Merle M. Plassmann, Caiza Persson, Ian T. Cousins, and Jonathan P. Benskin. 2019. “Release of Side-Chain Fluorinated Polymer-Containing Microplastic Fibers from Functional Textiles During Washing and First Estimates of Perfluoroalkyl Acid Emissions.” Environmental Science & Technology 53 (24):14329-14338. 10.1021/acs.est.9b04165.

Schellenberger, Steffen, Ioannis Liagkouridis, Raed Awad, Stuart Khan, Merle Plassmann, Gregory Peters, Jonathan P. Benskin, and Ian T. Cousins. 2022. “An Outdoor Aging Study to Investigate the Release of Per- And Polyfluoroalkyl Substances (PFAS) from Functional Textiles.” Environmental Science & Technology 56 (6):3471-3479. 10.1021/acs.est.1c06812.

Schenker, Urs, Martin Scheringer, Matthew MacLeod, Jonathan W. Martin, Ian T. Cousins, and Konrad Hungerbühler. 2008. “Contribution of Volatile Precursor Substances to the Flux of Perfluorooctanoate to the Arctic.” Environmental Science & Technology 42 (10):3710-3716. 10.1021/es703165m.

Scher, Deanna P., James E. Kelly, Carin A. Huset, Kitrina M. Barry, Richard W. Hoffbeck, Virginia L. Yingling, and Rita B. Messing. 2018. “Occurrence of perfluoroalkyl substances (PFAS) in garden produce at homes with a history of PFAS-contaminated drinking water.” Chemosphere 196:548-555. https://doi.org/10.1016/j.chemosphere.2017.12.179.

Scheringer, Martin, Xenia Trier, Ian T. Cousins, Pim de Voogt, Tony Fletcher, Zhanyun Wang, and Thomas F. Webster. 2014. “Helsingør Statement on poly- and perfluorinated alkyl substances (PFASs).” Chemosphere 114:337-339. https://doi.org/10.1016/j.chemosphere.2014.05.044.

Schroeder, Tim, David Bond, and Janet Foley. 2021. “PFAS soil and groundwater contamination via industrial airborne emission and land deposition in SW Vermont and Eastern New York State, USA.” Environmental Science: Processes & Impacts 23 (2):291-301. 10.1039/D0EM00427H.

Schuetze, Andrea, Thomas Heberer, Stefan Effkemann, and Susanne Juergensen. 2010. “Occurrence and assessment of perfluorinated chemicals in wild fish from Northern Germany.” Chemosphere 78 (6):647-652. https://doi.org/10.1016/j.chemosphere.2009.12.015.

Schultz, Melissa M., Douglas F. Barofsky, and Jennifer A. Field. 2004. “Quantitative Determination of Fluorotelomer Sulfonates in Groundwater by LC MS/MS.” Environmental Science & Technology 38 (6):1828-1835. 10.1021/es035031j.

Schultz, Melissa M., Christopher P. Higgins, Carin A. Huset, Richard G. Luthy, Douglas F. Barofsky, and Jennifer A. Field. 2006. “Fluorochemical Mass Flows in a Municipal Wastewater Treatment Facility.” Environmental Science & Technology 40 (23):7350-7357. 10.1021/es061025m.

Schulz, Katarina, Marcia R. Silva, and Rebecca Klaper. 2020. “Distribution and effects of branched versus linear isomers of PFOA, PFOS, and PFHxS: A review of recent literature.” Science of The Total Environment 733:139186. https://doi.org/10.1016/j.scitotenv.2020.139186.

Schümann, Michael, Hellmuth Lilienthal, and Jürgen Hölzer. 2021. “Human biomonitoring (HBM)-II values for perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) – Description, derivation and discussion.” Regulatory Toxicology and Pharmacology 121:104868. https://doi.org/10.1016/j.yrtph.2021.104868.

Schwarzenbach, R. P., P.M. Gschwend, and D.M. Imboden. 2003. Environmental Organic Chemistry, 2nd Edition. Hoboken, NJ: Wiley-Interscience. ISBN No. 0471357502.

Schwichtenberg, Trever, Dorin Bogdan, Courtney C. Carignan, Patrick Reardon, Justin Rewerts, Thomas Wanzek, and Jennifer A. Field. 2020. “PFAS and Dissolved Organic Carbon Enrichment in Surface Water Foams on a Northern U.S. Freshwater Lake.” Environmental Science & Technology 54 (22):14455-14464. https://doi.org/10.1016/j.yrtph.2021.104868.

Science History Institute. 2017. “Historical Biography: Roy J. Plunkett.” Last Modified December 14, 2017. accessed 2021. https://www.sciencehistory.org/historical-profile/roy-j-plunkett.

Scott, Brian F., Cheryl A. Moody, Christine Spencer, Jeffrey M. Small, Derek C. G. Muir, and Scott A. Mabury. 2006. “Analysis for Perfluorocarboxylic Acids/Anions in Surface Waters and Precipitation Using GC−MS and Analysis of PFOA from Large-Volume Samples.” Environmental Science & Technology 40 (20):6405-6410. https://doi.org/10.1021/es061131o.

Seacat, A. M., P. J. Thomford, K. J. Hansen, G. W. Olsen, M. T. Case, and J. L. Butenhoff. 2002. “Subchronic toxicity studies on perfluorooctanesulfonate potassium salt in cynomolgus monkeys.” Toxicol Sci 68 (1):249-64. 10.1093/toxsci/68.1.249.

Sedlak, Margaret, Jonathan P. Benskin, Adam Wong, Richard Grace, and Denise Greig. 2017. “Per- and polyfluoroalkyl substances (PFASs) in San Francisco Bay wildlife: Temporal trends, exposure pathways, and notable presence of precursor compounds.” Chemosphere 185:1217-1226. https://doi.org/10.1016/j.chemosphere.2017.04.096.

Sedlak, Margaret D., and Denise J. Greig. 2012. “Perfluoroalkyl compounds (PFCs) in wildlife from an urban estuary.” Journal of Environmental Monitoring 14 (1):146-154. 10.1039/C1EM10609K.

Sehmel, G. A. 1984. Deposition and Resuspension. Atmospheric Science and Power Production. Report DOE/TIC-27601: U.S. Department of Energy.

Šejna, M., J. Šimůnek, and M. Th. van Genuchten. 2022. The HYDRUS Software Package for Simulating One-, Two- and Three-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Porous Media, User Manual. Version 5.0. Prague, Czech Republic: PC Progress.

Sekiguchi, Kazuhiko, Takahisa Kudo, and Kenshi Sankoda. 2017. “Combined sonochemical and short-wavelength UV degradation of hydrophobic perfluorinated compounds.” Ultrasonics Sonochemistry 39:87-92. https://doi.org/10.1016/j.ultsonch.2017.04.002.

Seltenrich, Nate. “Guiding Communities Affected by PFASs: Tools for Tackling Contaminated Drinking Water.” Environmental Health Perspectives 127 (2):024003. 10.1289/EHP4170.

Seo, Sung-Hee, Min-Hui Son, Eun-Su Shin, Sung-Deuk Choi, and Yoon-Seok Chang. 2019. “Matrix-specific distribution and compositional profiles of perfluoroalkyl substances (PFASs) in multimedia environments.” Journal of Hazardous Materials 364:19-27. https://doi.org/10.1016/j.jhazmat.2018.10.012.

Sepulvado, Jennifer G., Andrea C. Blaine, Lakhwinder S. Hundal, and Christopher P. Higgins. 2011. “Occurrence and Fate of Perfluorochemicals in Soil Following the Land Application of Municipal Biosolids.” Environmental Science & Technology 45 (19):8106-8112. https://doi.org/10.1021/es103903d.

SERDP-ESTCP. 2017. In Situ and Ex Situ Remediation of Per- and Polyfluoroalkyl Substance Contaminated Groundwater. FY Statement of Need. Environmental Restoration Program Area. https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Contaminated-Groundwater-SONs/PFAS-Remediation/(language)/eng-US.

SERDP-ESTCP. 2017. Summary Report: SERDP and ESTCP Workshop on Research and Demonstration Needs for Management of AFFF-Impacted Sites.

SERDP-ESTCP. 2018. Removal and Destruction of PFAS and Co-contaminants from Groundwater. ER18-5015. www.serdp-estcp.org.

SERDP-ESTCP. 2019. “Per- and Polyfluoroalkyl Substances (PFASs).” accessed 2021. https://www.serdp-estcp.org/Featured-Initiatives/Per-and-Polyfluoroalkyl-Substances-PFASs.

SERDP-ESTCP. 2020. Supercritical Water Oxidation (SCWO) for Complete PFAS Destruction. ER20-5350. https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/ER20-5350/(language)/eng-US.

SERDP-ESTCP. 2021. Development and Validation of Novel Techniques to Assess Leaching and Mobility of Per and Polyfluoroalkyl Substances (PFAS) in Impacted Media. ER-1126.

https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER20-1126.

Serex, Tessa, Satheesh Anand, Susan Munley, E. Maria Donner, Steven R. Frame, Robert C. Buck, and Scott E. Loveless. 2014. “Toxicological evaluation of 6:2 fluorotelomer alcohol.” Toxicology 319:1-9. https://doi.org/10.1016/j.tox.2014.01.009.

SFB RWQCB. 2020. Transmittal of Interim Final Environmental Screening Levels (ESLs) for Two Per- and Polyfluoroalkyl Substances (PFAS): Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoate (PFOA). https://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/ESL/PFAS_ESL_Memo.pdf.

Sha, Bo, Jana H. Johansson, Peter Tunved, Pernilla Bohlin-Nizzetto, Ian T. Cousins, and Matthew E. Salter. 2022. “Sea Spray Aerosol (SSA) as a Source of Perfluoroalkyl Acids (PFAAs) to the Atmosphere: Field Evidence from Long-Term Air Monitoring.” Environmental Science & Technology 56 (1):228-238. 10.1021/acs.est.1c04277.

Shan, G., M. Wei, L. Zhu, Z. Liu, and Y. Zhang. 2014. “Concentration profiles and spatial distribution of perfluoroalkyl substances in an industrial center with condensed fluorochemical facilities.” Science of The Total Environment 490:351-9. https://doi.org/10.1016/j.scitotenv.2014.05.005.

Sharifan, Hamidreza, Majid Bagheri, Dan Wang, Joel G. Burken, Christopher P. Higgins, Yanna Liang, Jinxia Liu, Charles E. Schaefer, and Jens Blotevogel. 2021. “Fate and transport of per- and polyfluoroalkyl substances (PFASs) in the vadose zone.” Science of The Total Environment 771:145427. https://doi.org/10.1016/j.scitotenv.2021.145427.

Sharma, Brij Mohan, Girija K. Bharat, Shresth Tayal, Thorjørn Larssen, Jitka Bečanová, Pavlína Karásková, Paul G. Whitehead, Martyn N. Futter, Dan Butterfield, and Luca Nizzetto. 2016. “Perfluoroalkyl substances (PFAS) in river and ground/drinking water of the Ganges River basin: Emissions and implications for human exposure.” Environmental Pollution 208:704-713. https://doi.org/10.1016/j.envpol.2015.10.050.

Sharp, Simon, Paula Sardiña, Leon Metzeling, Rob McKenzie, Paul Leahy, Peter Menkhorst, and Andrea Hinwood. 2021. “Per- and Polyfluoroalkyl Substances in Ducks and the Relationship with Concentrations in Water, Sediment, and Soil.” Environmental Toxicology and Chemistry 40 (3):846-858. https://doi.org/10.1002/etc.4818.

Shearer, Joseph J., Catherine L. Callahan, Antonia M. Calafat, Wen-Yi Huang, Rena R. Jones, Venkata S. Sabbisetti, Neal D. Freedman, Joshua N. Sampson, Debra T. Silverman, Mark P. Purdue, and Jonathan N. Hofmann. 2021. “Serum Concentrations of Per- and Polyfluoroalkyl Substances and Risk of Renal Cell Carcinoma.” JNCI: Journal of the National Cancer Institute 113 (5):580-587. https://doi.org/10.1093/jnci/djaa143.

Sheinson, R.S., and B.A. Williams. 2007. Preventing Hydrogen Sulfide Generation in Shipboard Fire Protection Systems. Code 6185: Navy Technology Center for Safety & Survivability Naval Research Laboratory.

Sheng, Nan, Yitao Pan, Yong Guo, Yan Sun, and Jiayin Dai. 2018. “Hepatotoxic Effects of Hexafluoropropylene Oxide Trimer Acid (HFPO-TA), A Novel Perfluorooctanoic Acid (PFOA) Alternative, on Mice.” Environmental Science & Technology 52 (14):8005-8015. https://doi.org/10.1021/acs.est.8b01714.

Sheng, Nan, Xiujuan Zhou, Fei Zheng, Yitao Pan, Xuejiang Guo, Yong Guo, Yan Sun, and Jiayin Dai. 2017. “Comparative hepatotoxicity of 6:2 fluorotelomer carboxylic acid and 6:2 fluorotelomer sulfonic acid, two fluorinated alternatives to long-chain perfluoroalkyl acids, on adult male mice.” Archives of Toxicology 91 (8):2909-2919. 10.1007/s00204-016-1917-2.

Shi, Guohui, Qianqian Cui, Yitao Pan, Nan Sheng, Sujie Sun, Yong Guo, and Jiayin Dai. 2017. “6:2 Chlorinated polyfluorinated ether sulfonate, a PFOS alternative, induces embryotoxicity and disrupts cardiac development in zebrafish embryos.” Aquatic Toxicology 185:67-75. https://doi.org/10.1016/j.aquatox.2017.02.002.

Shi, Guohui, Qianqian Cui, Jinxing Wang, Hua Guo, Yitao Pan, Nan Sheng, Yong Guo, and Jiayin Dai. 2019. “Chronic exposure to 6:2 chlorinated polyfluorinated ether sulfonate acid (F-53B) induced hepatotoxic effects in adult zebrafish and disrupted the PPAR signaling pathway in their offspring.” Environmental Pollution 249:550-559. https://doi.org/10.1016/j.envpol.2019.03.032.

Shi, Guohui, Hua Guo, Nan Sheng, Qianqian Cui, Yitao Pan, Jinxing Wang, Yong Guo, and Jiayin Dai. 2018. “Two-generational reproductive toxicity assessment of 6:2 chlorinated polyfluorinated ether sulfonate (F-53B, a novel alternative to perfluorooctane sulfonate) in zebrafish." Environmental Pollution 243:1517-1527. https://doi.org/10.1016/j.envpol.2018.09.120.

Shi, Guohui, Jinxing Wang, Hua Guo, Nan Sheng, Qianqian Cui, Yitao Pan, Yong Guo, Yan Sun, and Jiayin Dai. 2019. "Parental exposure to 6:2 chlorinated polyfluorinated ether sulfonate (F-53B) induced transgenerational thyroid hormone disruption in zebrafish." Science of The Total Environment 665:855-863. https://doi.org/10.1016/j.scitotenv.2019.02.198.

Shi, Yali, Robin Vestergren, Lin Xu, Xiaowei Song, Xiameng Niu, Chunhui Zhang, and Yaqi Cai. 2015. "Characterizing direct emissions of perfluoroalkyl substances from ongoing fluoropolymer production sources: A spatial trend study of Xiaoqing River, China." Environmental Pollution 206:104-112. https://doi.org/10.1016/j.envpol.2015.06.035.

Shi, Yali, Robin Vestergren, Lin Xu, Zhen Zhou, Chuangxiu Li, Yong Liang, and Yaqi Cai. 2016. "Human Exposure and Elimination Kinetics of Chlorinated Polyfluoroalkyl Ether Sulfonic Acids (Cl-PFESAs)." Environmental Science & Technology 50 (5):2396-2404. 10.1021/acs.est.5b05849.

Shi, Yali, Robin Vestergren, Zhen Zhou, Xiaowei Song, Lin Xu, Yong Liang, and Yaqi Cai. 2015. "Tissue Distribution and Whole Body Burden of the Chlorinated Polyfluoroalkyl Ether Sulfonic Acid F-53B in Crucian Carp (Carassius carassius): Evidence for a Highly Bioaccumulative Contaminant of Emerging Concern." Environmental Science & Technology 49 (24):14156-14165. 10.1021/acs.est.5b04299.

Shi, Z., L. Ding, H. Zhang, Y. Feng, M. Xu, and J. Dai. 2009. "Chronic exposure to perfluorododecanoic acid disrupts testicular steroidogenesis and the expression of related genes in male rats." Toxicol Lett 188 (3):192-200. 10.1016/j.toxlet.2009.04.014.

Shi, Z., H. Zhang, L. Ding, Y. Feng, M. Xu, and J. Dai. 2009. "The effect of perfluorododecanonic acid on endocrine status, sex hormones and expression of steroidogenic genes in pubertal female rats." Reprod Toxicol 27 (3-4):352-359. 10.1016/j.reprotox.2009.02.008.

Shin, Hyeong-Moo, P. B. Ryan, V. M. Vieira, and S. M. Bartell. 2012. "Modeling the air-soil transport pathway of perfluorooctanoic acid in the mid-Ohio Valley using linked air dispersion and vadose zone models." Atmospheric Environment 51:67-74. https://doi.org/10.1016/j.atmosenv.2012.01.049.

Shin, Hyeong-Moo, Verónica M. Vieira, P. Barry Ryan, Russell Detwiler, Brett Sanders, Kyle Steenland, and Scott M. Bartell. 2011. "Environmental Fate and Transport Modeling for Perfluorooctanoic Acid Emitted from the Washington Works Facility in West Virginia." Environmental Science & Technology 45 (4):1435-1442. 10.1021/es102769t.

Shoeib, Mahiba, Tom Harner, Michael Ikonomou, and Kurunthachalam Kannan. 2004. "Indoor and Outdoor Air Concentrations and Phase Partitioning of Perfluoroalkyl Sulfonamides and Polybrominated Diphenyl Ethers." Environmental Science & Technology 38 (5):1313-1320. 10.1021/es0305555.

Shoeib, Mahiba, Tom Harner, Glenys M. Webster, and Sum Chi Lee. 2011. "Indoor Sources of Poly- and Perfluorinated Compounds (PFCS) in Vancouver, Canada: Implications for Human Exposure." Environmental Science & Technology 45 (19):7999-8005. 10.1021/es103562v.

Shoeib, Mahiba, Penny Vlahos, Tom Harner, Andrew Peters, Margaret Graustein, and Julie Narayan. 2010. "Survey of polyfluorinated chemicals (PFCs) in the atmosphere over the northeast Atlantic Ocean." Atmospheric Environment 44 (24):2887-2893. https://doi.org/10.1016/j.atmosenv.2010.04.056.

Shojaei, Marzieh, Abigail S. Joyce, P. Lee Ferguson, and Jennifer L. Guelfo. 2022. "Novel per- and polyfluoroalkyl substances in an active-use C6-based aqueous film forming foam." Journal of Hazardous Materials Letters 3:100061. https://doi.org/10.1016/j.hazl.2022.100061.

Shojaei, Marzieh, Naveen Kumar, Suparada Chaobol, Ke Wu, Michelle Crimi, and Jennifer Guelfo. 2021. "Enhanced Recovery of Per- and Polyfluoroalkyl Substances (PFASs) from Impacted Soils Using Heat Activated Persulfate." Environmental Science & Technology 55 (14):9805-9816. 10.1021/acs.est.0c08069.

SIA. 2008. Use of PFAS/PFOA Compounds by USSIA Members in 2008. http://www.sematech.org/docubase/document/PFOS_Survey_2009_final.pdf

SIA. 2023. The Impact of a Potential PFAS Restriction on the Semiconductor Sector. SIA PFAS Consortium.https://www.semiconductors.org.

SIA. 2023. Background on Semiconductor Manufacturing and PFAS. SIA Semiconductor PFAS Consortium.https://www.semiconductors.org.

Sibinski, L.J. 1987. Final report of a two-year oral (diet) toxicity and carcinogenicity study of fluorochemical FC-143 (perfluorooctanoate ammonium carboxylate) in rats. Vol. 1-4. No.0281CR0012; 8EHQ-1087-0394: 3M Company/RIKER.

Siegrist, R.L., M. Crimi, and T.J. Simpkin. 2011. In situ Chemical Oxidation for Groundwater Remediation. Edited by R.L. Siegrist, M. Crimi and T.J. Simpkin. Vol. 3, SERDP ESTCP Environmental Remediation Technology. New York: Springer-Verlag. ISBN No. 78-1-4419-7825-7.

Sigma-Aldrich web page. 2018. “Sigma-Aldrich web page.” http://www.sigmaaldrich.com/united-states.html

Silent Spring Institute. 2022. “Digital Exposure Report-Back Interface(DERBI).” accessed 2023. https://silentspring.org/project/digital-exposure-report-back-interface-derbi.

Silva, Jeff A., Jiří Šimůnek, and John E. McCray. 2020. “A Modified HYDRUS Model for Simulating PFAS Transport in the Vadose Zone.” Water 12 (10). https://doi.org/10.3390/w12102758.

Silva, Jeff A. K., William A. Martin, Jared L. Johnson, and John E. McCray. 2019. “Evaluating air-water and NAPL-water interfacial adsorption and retention of Perfluorocarboxylic acids within the Vadose zone.” Journal of Contaminant Hydrology 223:103472. https://doi.org/10.1016/j.jconhyd.2019.03.004.

Silva, Jeff A. K., William A. Martin, and John E. McCray. 2021. “Air-water interfacial adsorption coefficients for PFAS when present as a multi-component mixture.” Journal of Contaminant Hydrology 236:103731. https://doi.org/10.1016/j.jconhyd.2020.103731.

Sima, Matthew W., and Peter R. Jaffé. 2021. “A critical review of modeling Poly- and Perfluoroalkyl Substances (PFAS) in the soil-water environment.” Science of The Total Environment 757:143793. https://doi.org/10.1016/j.scitotenv.2020.143793.

Simon, John A., Stew Abrams, Tim Bradburne, Dan Bryant, Matthew Burns, Daniel Cassidy, John Cherry, Sheau-Yun Chiang, Douglas Cox, Michelle Crimi, Elizabeth Denly, Bill DiGuiseppi, Jim Fenstermacher, Stephanie Fiorenza, Joseph Guarnaccia, Nathan Hagelin, Linda Hall, John Hesemann, Erika Houtz, Stephen S. Koenigsberg, Francois Lauzon, Jeffrey Longsworth, Tom Maher, Angus McGrath, Ravi Naidu, Charles J. Newell, Beth L. Parker, Tadbir Singh, Paul Tomiczek, and Rick Wice. 2019. “PFAS Experts Symposium: Statements on regulatory policy, chemistry and analtyics, toxicology, transport/fate, and remediation for per- and polyfluoroalkyl substances (PFAS) contamination issues.” Remediation Journal 29 (4):31-48. 10.1002/rem.21624.

Simpson, Stuart L., Yawen Liu, David A. Spadaro, Xinhong Wang, Rai S. Kookana, and Graeme E. Batley. 2021. “Chronic effects and thresholds for estuarine and marine benthic organism exposure to perfluorooctane sulfonic acid (PFOS)-contaminated sediments: Influence of organic carbon and exposure routes.” Science of The Total Environment 776:146008. https://doi.org/10.1016/j.scitotenv.2021.146008.

Šimůnek, J., M. Šejna, G. Brunetti, and M. Th. van Genuchten. 2022. The HYDRUS Software Package for Simulating the One-, Two, and Three-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media. Technical Manual I, Hydrus 1D. Version 5.0. Prague, Czech Republic: PC Progress.

Šimůnek, J., M. Th. van Genuchten, and M. Šejna. 2022. The HYDRUS Software Package for Simulating One-, Two-, and Three-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Porous Media, Technical Manual II, Hydrus 2D/3D. Version 5.0. Prague, Czech Republic: PC Progress.

Sinclair, A., and A. Diduck. 2009. “Public participation in Canadian environmental assessment: enduring challenges and future directions.” In Environmental impact assessment: practice and participation, Second edition, edited by K. Hanna, 58-82. Ontario: Oxford University Press. ISBN No. 9780195430226.

Sinclair, Ewan, and Kurunthachalam Kannan. 2006. “Mass Loading and Fate of Perfluoroalkyl Surfactants in Wastewater

Treatment Plants." Environmental Science & Technology 40 (5):1408-1414. 10.1021/es051798v.

Sindermann, A. B., J. R. Porch, H. O. Krueger, and R. L. Van Hoven. 2002. PFOS: an acute toxicity study with the earthworm in an artificial soil substrate. edited by Project No. 454-11. EPA Docket AR226-1106. Easton, MD.: Wildlife International Ltd.

Singh, Gurbir, Gurpreet Kaur, Karl Williard, Jon Schoonover, and Jasjit Kang. 2018. "Monitoring of Water and Solute Transport in the Vadose Zone: A Review." Vadose Zone Journal 17 (1):160058. https://doi.org/10.2136/vzj2016.07.0058.

Singh, Raj Kamal, Sujan Fernando, Sadjad Fakouri Baygi, Nicholas Multari, Selma Mededovic Thagard, and Thomas M. Holsen. 2019. "Breakdown Products from Perfluorinated Alkyl Substances (PFAS) Degradation in a Plasma-Based Water Treatment Process." Environmental Science & Technology 53 (5):2731-2738. 10.1021/acs.est.8b07031.

Singh, Raj Kamal, Nicholas Multari, Chase Nau-Hix, Richard H. Anderson, Stephen D. Richardson, Thomas M. Holsen, and Selma Mededovic Thagard. 2019. "Rapid Removal of Poly- and Perfluorinated Compounds from Investigation-Derived Waste (IDW) in a Pilot-Scale Plasma Reactor." Environmental Science & Technology 53 (19):11375-11382. 10.1021/acs.est.9b02964.

Singh, Shilpi, and Shio Kumar Singh. 2018. "Prepubertal exposure to perfluorononanoic acid interferes with spermatogenesis and steroidogenesis in male mice." Ecotoxicology and Environmental Safety 170:590-599. 10.1016/j.ecoenv.2018.12.034.

Singh, Shilpi, and Shio Kumar Singh. 2019. "Chronic exposure to perfluorononanoic acid impairs spermatogenesis, steroidogenesis and fertility in male mice." Journal of Applied Toxicology 39 (3):420-431. 10.1002/jat.3733.

Siros, S.M. 2018. "New Law Requires Widespread Testing for Unregulated Contaminants." Corporate Environmental Lawyer, Jenner & Block. accessed 2021. https://environblog.jenner.com/corporate_environmental_l/2018/10/new-law-requires-widespread-testing-for-unregulated-contaminants.html.

Skaar, Jøran Solnes, Erik Magnus Ræder, Jan Ludvig Lyche, Lutz Ahrens, and Roland Kallenborn. 2019. "Elucidation of contamination sources for poly- and perfluoroalkyl substances (PFASs) on Svalbard (Norwegian Arctic)." Environmental Science and Pollution Research 26 (8):7356-7363. 10.1007/s11356-018-2162-4.

Skutlarek, D., M. Exner, and H. Farber. 2006. "Perfluorinated surfactants in surface and drinking waters." Environ Sci Pollut Res Int 13 (5):299-307.

Slinn, W.G.N. 1984. Precipitation Scavenging. Atmospheric Science and Power Production. Report DOE/TIC-27601: U.S. Department of Energy.

Slovic, P. 1987. "Perception of Risk." Science 236 (4799):280-285. https://doi.org/10.1126/science.3563507.

Slovic, P. 1997. "Public Perception of Risk." Journal of Environmental Health 59 (9):22-25.

Slovic, Paul. 2003. "Going Beyond the Red Book: The Sociopolitics of Risk." Human and Ecological Risk Assessment: An International Journal 9 (5):1181-1190. 10.1080/10807030390244577.

Slovic, Paul, Baruch Fischhoff, and Sarah Lichtenstein. 1982. "Why Study Risk Perception?" Risk Analysis 2 (2):83-93. 10.1111/j.1539-6924.1982.tb01369.x.

Smith, J. W. N., B. Beuthe, M. Dunk, S. Demeure, J. M. M. Carmona, A. Medve, M. J. Spence, Tessa Pancras, G. Schrauwen, Thomas Held, K. Baker, Ian Ross, and Hans Slenders. 2016. Environmental fate and effects of poly and perfluoroalkyl substances (PFAS). 8/16: CONCAWE Reports. https://www.concawe.eu.

Smith, Sanne J., Melanie Lauria, Lutz Ahrens, Philip McCleaf, Patrik Hollman, Sofia Bjälkefur Seroka, Timo Hamers, Hans Peter H. Arp, and Karin Wiberg. 2023. "Electrochemical Oxidation for Treatment of PFAS in Contaminated Water and Fractionated Foam─A Pilot-Scale Study." ACS ES&T Water 3 (4):1201-1211. 10.1021/acsestwater.2c00660.

Smith, Sanne J., Jeffrey Lewis, Karin Wiberg, Erik Wall, and Lutz Ahrens. 2023. "Foam fractionation for removal of per- and polyfluoroalkyl substances: Towards closing the mass balance." Science of The Total Environment 871:162050.

https://doi.org/10.1016/j.scitotenv.2023.162050.

Smith, Samantha J., David G. Wahman, Eric J. Kleiner, Gulizhaer Abulikemu, Eva K. Stebel, Brooke N. Gray, Boris Datsov, Brian C. Crone, Rose D. Taylor, Erika Womack, Cameron X. Gastaldo, George Sorial, Darren Lytle, Jonathan G. Pressman, and Levi M. Haupert. 2023. "Anion Exchange Resin and Inorganic Anion Parameter Determination for Model Validation and Evaluation of Unintended Consequences during PFAS Treatment." ACS ES&T Water 3 (2):576-587. 10.1021/acsestwater.2c00572.

Smith, Sanne J., Karin Wiberg, Philip McCleaf, and Lutz Ahrens. 2022. "Pilot-Scale Continuous Foam Fractionation for the Removal of Per- and Polyfluoroalkyl Substances (PFAS) from Landfill Leachate." ACS ES&T Water 2 (5):841-851. 10.1021/acsestwater.2c00032.

Smithwick, Marla, Scott A. Mabury, Keith R. Solomon, Christian Sonne, Jonathan W. Martin, Erik W. Born, Rune Dietz, Andrew E. Derocher, Robert J. Letcher, Thomas J. Evans, Geir W. Gabrielsen, John Nagy, Ian Stirling, Mitch K. Taylor, and Derek C. G. Muir. 2005. "Circumpolar Study of Perfluoroalkyl Contaminants in Polar Bears (Ursus maritimus)." Environmental Science & Technology 39 (15):5517-5523. 10.1021/es048309w.

Smithwick, Marla, Derek C. G. Muir, Scott A. Mabury, Keith R. Solomon, Jonathan W. Martin, Christian Sonne, Erik W. Born, Robert J. Letcher, and Rune Dietz. 2005. "Perfluoroalkyl contaminants in liver tissue from East Greenland polar bears (Ursus maritimus)." Environmental Toxicology and Chemistry 24 (4):981-986. 10.1897/04-258R.1.

Snyder, S. A., E.C. Wert, H.X. Lei, P. Westerhoff, and Y. Yoon. 2007. Removal of EDCs and Pharmaceuticals in Drinking and Reuse Treatment Processes. Denver, Colorado: AWWA Research Foundation.

Sobolewski, M., K. Conrad, J. L. Allen, H. Weston, K. Martin, B. P. Lawrence, and D. A. Cory-Slechta. 2014. "Sex-specific enhanced behavioral toxicity induced by maternal exposure to a mixture of low dose endocrine-disrupting chemicals." Neurotoxicology 45:121-30. 10.1016/j.neuro.2014.09.008.

Söderqvist, Tore, Petra Brinkhoff, Tommy Norberg, Lars Rosén, Pär-Erik Back, and Jenny Norrman. 2015. "Cost-benefit analysis as a part of sustainability assessment of remediation alternatives for contaminated land." Journal of Environmental Management 157:267-278. https://doi.org/10.1016/j.jenvman.2015.04.024.

Solo-Gabriele, Helena M., Athena S. Jones, Andrew B. Lindstrom, and Johnsie R. Lang. 2020. "Waste type, incineration, and aeration are associated with per- and polyfluoroalkyl levels in landfill leachates." Waste Management 107:191-200. https://doi.org/10.1016/j.wasman.2020.03.034.

Solvay. 2019. Letter from Solvay to Greg Schweer, Office of Pollution Prevention and Toxics, USEPA, December 23, 2019. https://foiaonline.gov/foiaonline/api/request/downloadFile/Study%209.pdf/15a2e80d-ee08-432f-8eec-39b03d584ebf.

Somasundaran, P., Thomas W. Healy, and D. W. Fuerstenau. 1964. "Surfactant Adsorption at the Solid—Liquid Interface—Dependence of Mechanism on Chain Length." The Journal of Physical Chemistry 68 (12):3562-3566. https://doi.org/10.1021/j100794a021.

Son, H. Y., S. H. Kim, H. I. Shin, H. I. Bae, and J. H. Yang. 2008. "Perfluorooctanoic acid-induced hepatic toxicity following 21-day oral exposure in mice." Arch Toxicol 82 (4):239-46. 10.1007/s00204-007-0246-x.

Son, H. Y., S. Lee, E. N. Tak, H. S. Cho, H. I. Shin, S. H. Kim, and J. H. Yang. 2009. "Perfluorooctanoic acid alters T lymphocyte phenotypes and cytokine expression in mice." Environ Toxicol 24 (6):580-8. 10.1002/tox.20459.

Song, Shuang, Jiaqi Fan, Zhiqiao He, Liyong Zhan, Zhiwu Liu, Jianmeng Chen, and Xinhua Xu. 2010. "Electrochemical degradation of azo dye C.I. Reactive Red 195 by anodic oxidation on Ti/SnO2–Sb/PbO2 electrodes." Electrochimica Acta 55 (11):3606-3613. https://doi.org/10.1016/j.electacta.2010.01.101.

Song, Yinan, Deyi Hou, Junli Zhang, David O'Connor, Guanghe Li, Qingbao Gu, Shupeng Li, and Peng Liu. 2018. "Environmental and socio-economic sustainability appraisal of contaminated land remediation strategies: A case study at a mega-site in China." Science of The Total Environment 610-611:391-401. https://doi.org/10.1016/j.scitotenv.2017.08.016.

Song, Zhou, Heqing Tang, Nan Wang, and Lihua Zhu. 2013. "Reductive defluorination of perfluorooctanoic acid by hydrated electrons in a sulfite-mediated UV photochemical system." Journal of Hazardous Materials 262:332-338.

https://doi.org/10.1016/j.jhazmat.2013.08.059.

Sörengård, Mattias, Dan B. Kleja, and Lutz Ahrens. 2019. “Stabilization and solidification remediation of soil contaminated with poly- and perfluoroalkyl substances (PFASs).” Journal of Hazardous Materials 367:639-646. https://doi.org/10.1016/j.jhazmat.2019.01.005.

Sörengård, Mattias, Erik Östblom, Stephan Köhler, and Lutz Ahrens. 2020. “Adsorption behavior of per- and polyfluoralkyl substances (PFASs) to 44 inorganic and organic sorbents and use of dyes as proxies for PFAS sorption.” Journal of Environmental Chemical Engineering 8 (3):103744. https://doi.org/10.1016/j.jece.2020.103744.

Sörengård, Mattias, I. Travar, Dan B Kleja, and Lutz Ahrens. 2022. “Fly Ash-Based Waste for Ex-Situ Landfill Stabilization of Per- and Polyfluoroalkyl Substance (Pfas)-Contaminated Soil.” Chemical Engineering Journal Advances 12:100396.

Soriano, Álvaro, Daniel Gorri, and Ane Urtiaga. 2017. “Efficient treatment of perfluorohexanoic acid by nanofiltration followed by electrochemical degradation of the NF concentrate.” Water Research 112:147-156. https://doi.org/10.1016/j.watres.2017.01.043.

Soriano, Alvaro, Charles Schaefer, and Ane Urtiaga. 2020. “Enhanced treatment of perfluoroalkyl acids in groundwater by membrane separation and electrochemical oxidation.” Chemical Engineering Journal Advances 4:100042. https://doi.org/10.1016/j.ceja.2020.100042.

Sørli, Jorid B., Marit Låg, Leni Ekeren, Jesus Perez-Gil, Line S. Haug, Emilie Da Silva, Muhammad N. Matrod, Kristine B. Gützkow, and Birgitte Lindeman. 2020. “Per- and polyfluoroalkyl substances (PFASs) modify lung surfactant function and pro-inflammatory responses in human bronchial epithelial cells.” Toxicology in Vitro 62:104656. https://doi.org/10.1016/j.tiv.2019.104656.

Stahl, Leanne L., Blaine D. Snyder, Anthony R. Olsen, Thomas M. Kincaid, John B. Wathen, and Harry B. McCarty. 2014. “Perfluorinated compounds in fish from U.S. urban rivers and the Great Lakes.” Science of The Total Environment 499:185-195. https://doi.org/10.1016/j.scitotenv.2014.07.126.

Stahl, T., J. Heyn, H. Thiele, J. Huther, K. Failing, S. Georgii, and H. Brunn. 2009. “Carryover of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) from soil to plants.” Archives of Environmental Contamination and Toxicology 57 (2):289-98. https://doi.org/10.1007/s00244-008-9272-9.

Stahl, Thorsten, Rika Alessa Riebe, Sandy Falk, Klaus Failing, and Hubertus Brunn. 2013. “Long-Term Lysimeter Experiment to Investigate the Leaching of Perfluoroalkyl Substances (PFASs) and the Carry-over from Soil to Plants: Results of a Pilot Study.” Journal of Agricultural and Food Chemistry 61 (8):1784-1793. https://doi.org/10.1021/jf305003h.

Staples, R.E., B.A. Burgess, and W.D. Kerns. 1984. “The embryo-fetal toxicity and teratogenic potential of ammonium perfluorooctanoate (APFO) in the rat.” Fundamental & Applied Toxicology 4:429-440.

State of Connecticut. 2022. State of Connecticut AFFF Take Back Program, Draining and Rinsing AFFF from Municipal On-Board Systems.

State of Virginia. 2019. Section 9.1-207.1 Firefighting foam management. Richmond, VA. https://trackbill.com/bill/virginia-house-bill-2762-firefighting-foam-management-use-of-foam-that-contains-pfas-chemicals/1640449/.

Steenland, K., V. Barry, and D. Savitz. 2018. “Serum Perfluorooctanoic Acid and Birthweight: An Updated Meta-Analysis with Bias Analysis.” Epidemiology 29 (6):765-776. https://doi.org/10.1097/ede.0000000000000903.

Steenland, Kyle, Tony Fletcher, Cheryl R. Stein, Scott M. Bartell, Lyndsey Darrow, Maria-Jose Lopez-Espinosa, P. Barry Ryan, and David A. Savitz. 2020. “Review: Evolution of evidence on PFOA and health following the assessments of the C8 Science Panel.” Environment International 145:106125. https://doi.org/10.1016/j.envint.2020.106125.

Steenland, Kyle, Chuangfang Jin, Jessica MacNeil, Cathy Lally, Alan Ducatman, Veronica Vieira, and Tony Fletcher. 2009. “Predictors of PFOA levels in a community surrounding a chemical plant.” Environmental health perspectives 117 (7):1083-1088. 10.1289/ehp.0800294.

Steenland, Kyle, Sarah Tinker, Stephanie Frisbee, Alan Ducatman, and Viola Vaccarino. 2009. “Association of Perfluorooctanoic Acid and Perfluorooctane Sulfonate With Serum Lipids Among Adults Living Near a Chemical Plant.” American Journal of Epidemiology 170 (10):1268-1278. 10.1093/aje/kwp279.

Steenland, K., and S. Woskie. 2012. “Cohort mortality study of workers exposed to perfluorooctanoic acid.” Am J Epidemiol 176 (10):909-17. 10.1093/aje/kws171.

Stefani, F., M. Rusconi, S. Valsecchi, and L. Marziali. 2014. “Evolutionary ecotoxicology of perfluoralkyl substances (PFASs) inferred from multigenerational exposure: a case study with Chironomus riparius (Diptera, Chironomidae).” Aquat Toxicol 156:41-51. 10.1016/j.aquatox.2014.07.020.

Steffens, Sophia D., Emily K. Cook, David L. Sedlak, and Lisa Alvarez-Cohen. 2021. “Under-reporting Potential of Perfluorooctanesulfonic Acid (PFOS) under High-Ionic Strength Conditions.” Environmental Science & Technology Letters 8 (12):1032-1037. 10.1021/acs.estlett.1c00762.

Stein, Cheryl R., David A. Savitz, and Marcelle Dougan. 2009. “Serum Levels of Perfluorooctanoic Acid and Perfluorooctane Sulfonate and Pregnancy Outcome.” American Journal of Epidemiology 170 (7):837-846. 10.1093/aje/kwp212.

Stein, C. R., M. S. Wolff, A. M. Calafat, K. Kato, and S. M. Engel. 2012. “Comparison of polyfluoroalkyl compound concentrations in maternal serum and amniotic fluid: a pilot study.” Reprod Toxicol 34 (3):312-6. 10.1016/j.reprotox.2012.05.039.

Steinle-Darling, Eva, and Martin Reinhard. 2008. “Nanofiltration for Trace Organic Contaminant Removal: Structure, Solution, and Membrane Fouling Effects on the Rejection of Perfluorochemicals.” Environmental Science & Technology 42 (14):5292-5297. 10.1021/es703207s.

Stevens, J.B., and A. Coryell. 2007. Surface water quality criterion for perfluorooctane sulfonic acid. STS Project 200604796. St. Paul, MN: Minnesota Pollution Control Agency.

Stevens, J.B., and A. Coryell. 2007. Surface Water Quality Criterion for Perfluorooctanoic Acid. STS Project 200604 796. St. Paul, MN: Minnesota Pollution Control Agency.

Stevenson, Charlotte N., Laura A. MacManus-Spencer, Till Luckenbach, Richard G. Luthy, and David Epel. 2006. “New Perspectives on Perfluorochemical Ecotoxicology: Inhibition and Induction of an Efflux Transporter in the Marine Mussel, Mytilus californianus.” Environmental Science & Technology 40 (17):5580-5585. 10.1021/es0602593.

Stevenson, P., and X. Li. 2014. Foam Fractionation. Principles and Process Design. First ed: CRC Press. ISBN No. 9780429098000. https://doi.org/10.1201/b16483.

Stewart, R. 2017. “Immobilization and Safe Disposal of Aqueous Film Forming Foam (AFFF) Impacted Soil in Australia.” Battelle International Symposium on Bioremediation and Sustainable Environmental Technologies, Miami, Florida, May 22-25, 2017.

Stewart, R., C. Lawrence, and J. Kirk. 2016. “An Aluminum Hydroxide Formulation Outperforms Activated Carbon in Binding Shorter Chain Per- and Poly-Fluorinated Alkyl Substances (PFAS).” Tenth International Conference on Remediation and Recalcitrant Compounds, Palm Springs, California, May 2016.

Stewart, R., and R. McFarland. 2017. “Immobilization of Per- and Polyfluorinated Alkyl Substances (PFAS) in 14 Soils from Airport Sites across Australia.” Battelle International Symposium on Bioremediation and Sustainable Environmental Technologies, Miami, Florida, May 22-25, 2017.

Stock, Naomi L., Vasile I. Furdui, Derek C. G. Muir, and Scott A. Mabury. 2007. “Perfluoroalkyl Contaminants in the Canadian Arctic: Evidence of Atmospheric Transport and Local Contamination.” Environmental Science & Technology 41 (10):3529-3536. 10.1021/es062709x.

Stock, Naomi L., Fiona K. Lau, David A. Ellis, Jonathan W. Martin, Derek C. G. Muir, and Scott A. Mabury. 2004. “Polyfluorinated Telomer Alcohols and Sulfonamides in the North American Troposphere.” Environmental Science & Technology 38 (4):991-996. 10.1021/es034644t.

Stockholm Convention. 2001. Stockholm Convention on Persistent Organic Pollutants.

Stoiber, Tasha, Sydney Evans, and Olga V. Naidenko. 2020. “Disposal of products and materials containing per- and polyfluoroalkyl substances (PFAS): A cyclical problem.” Chemosphere 260:127659. https://doi.org/10.1016/j.chemosphere.2020.127659.

Stout, S.A., J.M. Leather, and W.E. Corl III. 2003. A User’s Guide for Determining the Sources of Contaminants in Sediments. Technical Report 1907. San Diego, CA: U.S. Navy Spawar Systems Center.

Stover, Richard L. 2013. “Industrial and brackish water treatment with closed circuit reverse osmosis.” Desalination and Water Treatment 51 (4-6):1124-1130. 10.1080/19443994.2012.699341.

Strathmann, T. 2018. “UV-sulfite Photochemical Destruction of PFAS.” Emerging Contaminants Summit, Westminster, Colorado, March 6-7, 2018.

Stratton, G. R., F. Dai, C. L. Bellona, T. M. Holsen, E. R. Dickenson, and S. Mededovic Thagard. 2017. “Plasma-Based Water Treatment: Efficient Transformation of Perfluoroalkyl Substances in Prepared Solutions and Contaminated Groundwater.” Environ Sci Technol 51 (3):1643-1648. 10.1021/acs.est.6b04215.

Strynar, Mark J., and Andrew B. Lindstrom. 2008. “Perfluorinated Compounds in House Dust from Ohio and North Carolina, USA.” Environmental Science & Technology 42 (10):3751-3756. 10.1021/es7032058.

Strynar, Mark J., Andrew B. Lindstrom, Shoji F. Nakayama, Peter P. Egeghy, and Laurence J. Helfant. 2012. “Pilot scale application of a method for the analysis of perfluorinated compounds in surface soils.” Chemosphere 86 (3):252-257. https://doi.org/10.1016/j.chemosphere.2011.09.036.

Stuchal, L., and S. Roberts. 2019. Development of Surface Water Screening Levels for PFOA and PFOS Based on the Protection of Human Health. Center for Environmental & Human Toxicology University of Florida.

Stulp, John R. 1995. “Social, Political, and Educational Factors Involved in Facilitating Municipal Waste Utilization.” In Agricultural Utilization of Urban and Industrial By-Products, 1-9, ASA Special Publications. ISBN No. 9780891183242.

Stump, D. G., J. F. Holson, S. R. Murphy, C. H. Farr, B. Schmit, and M. Shinohara. 2008. “An oral two-generation reproductive toxicity study of S-111-S-WB in rats.” Reprod Toxicol 25 (1):7-20. 10.1016/j.reprotox.2007.10.002.

Stylianou, Marios, Maria K. Björnsdotter, Per-Erik Olsson, Ingrid Ericson Jogsten, and Jana Jass. 2019. “Distinct transcriptional response of Caenorhabditis elegans to different exposure routes of perfluorooctane sulfonic acid.” Environmental Research 168:406-413. https://doi.org/10.1016/j.envres.2018.10.019.

Suh, C. H., N. K. Cho, C. K. Lee, C. H. Lee, D. H. Kim, J. H. Kim, B. C. Son, and J. T. Lee. 2011. “Perfluorooctanoic acid-induced inhibition of placental prolactin-family hormone and fetal growth retardation in mice.” Mol Cell Endocrinol 337 (1-2):7-15. 10.1016/j.mce.2011.01.009.

Sun, Mei, Elisa Arevalo, Mark Strynar, Andrew Lindstrom, Michael Richardson, Ben Kearns, Adam Pickett, Chris Smith, and Detlef R. U. Knappe. 2016. “Legacy and Emerging Perfluoroalkyl Substances Are Important Drinking Water Contaminants in the Cape Fear River Watershed of North Carolina.” Environmental Science & Technology Letters 3 (12):415-419. https://doi.org/10.1021/acs.estlett.6b00398.

Sundstrom, M., S. C. Chang, P. E. Noker, G. S. Gorman, J. A. Hart, D. J. Ehresman, A. Bergman, and J. L. Butenhoff. 2012. “Comparative pharmacokinetics of perfluorohexanesulfonate (PFHxS) in rats, mice, and monkeys.” Reprod Toxicol 33 (4):441-451. 10.1016/j.reprotox.2011.07.004.

Sutherland, C.A., and H. O. Krueger. 2001. A 96-hour toxicity test with the freshwater diatom (Navicula pelliculosa). Wildlife International Ltd. Project number 454A-112.

Synquest Laboratories. “Synquest Laboratories web page.” http://synquestlabs.com

Szabo, Drew, Madison R. Nuske, Jennifer L. Lavers, Jeff Shimeta, Mark P. Green, Raoul A. Mulder, and Bradley O. Clarke. 2022. “A baseline study of per- and polyfluoroalkyl substances (PFASs) in waterfowl from a remote Australian environment.” Science of The Total Environment 812:152528. https://doi.org/10.1016/j.scitotenv.2021.152528.

Szabo, J., J. Hall, J. Hall, M. Magnuson, S. Panguluri, and G. Meiners. 2017. Treatment of Perfluorinated Alkyl Substances in Wash Water using Granular Activated Carbon and Mixed Media. EPA/600/R-17/175: USEPA Office of Research and Development.

Takahashi, M., S. Ishida, M. Hirata-Koizumi, A. Ono, and A. Hirose. 2014. "Repeated dose and reproductive/developmental toxicity of perfluoroundecanoic acid in rats." J Toxicol Sci 39 (1):97-108.

Takeuchi, N., Y. Kitagawa, A. Kosugi, K. Tachibana, H. Obo, and K. Yasuoka. 2013. "Plasma-liquid interfacial reaction in decomposition of perfluoro surfactants." Journal of Physics D Applied Physics 47 (4):045203. https://doi.org/10.1088/0022-3727/47/4/045203.

Tan, X., G. Xie, X. Sun, Q. Li, W. Zhong, P. Qiao, X. Sun, W. Jia, and Z. Zhou. 2013. "High fat diet feeding exaggerates perfluorooctanoic acid-induced liver injury in mice via modulating multiple metabolic pathways." PLoS One 8 (4):e61409. 10.1371/journal.pone.0061409.

Tang, Chuyang Y., Q. Shiang Fu, Craig S. Criddle, and James O. Leckie. 2007. "Effect of Flux (Transmembrane Pressure) and Membrane Properties on Fouling and Rejection of Reverse Osmosis and Nanofiltration Membranes Treating Perfluorooctane Sulfonate Containing Wastewater." Environmental Science & Technology 41 (6):2008-2014. 10.1021/es062052f.

Tang, Chuyang Y., Q. Shiang Fu, A. P. Robertson, Craig S. Criddle, and James O. Leckie. 2006. "Use of Reverse Osmosis Membranes to Remove Perfluorooctane Sulfonate (PFOS) from Semiconductor Wastewater." Environmental Science & Technology 40 (23):7343-7349. 10.1021/es060831q.

Tang, Heqing, Qingqing Xiang, Min Lei, Jingchun Yan, Lihua Zhu, and Jing Zou. 2012. "Efficient degradation of perfluorooctanoic acid by UV–Fenton process." Chemical Engineering Journal 184:156-162. https://doi.org/10.1016/j.cej.2012.01.020.

Taniyasu, Sachi, Kurunthachalam Kannan, Leo W. Y. Yeung, Karen Y. Kwok, Paul K. S. Lam, and Nobuyoshi Yamashita. 2008. "Analysis of trifluoroacetic acid and other short-chain perfluorinated acids (C2–C4) in precipitation by liquid chromatography–tandem mass spectrometry: Comparison to patterns of long-chain perfluorinated acids (C5–C18)." Analytica Chimica Acta 619 (2):221-230. https://doi.org/10.1016/j.aca.2008.04.064.

Taniyasu, Sachi, Nobuyoshi Yamashita, Hyo-Bang Moon, Karen Y Kwok, Paul Lam, Yuichi Horii, Gert Petrick, and Kurunthachalam Kannan. 2013. "Does wet precipitation represent local and regional atmospheric transportation by perfluorinated alkyl substances?" Environment international 55:25-32. https://doi.org/10.1016/j.envint.2013.02.005.

Tao, Lin, Kurunthachalam Kannan, Chung M. Wong, Kathleen F. Arcaro, and John L. Butenhoff. 2008. "Perfluorinated Compounds in Human Milk from Massachusetts, U.S.A." Environmental Science & Technology 42 (8):3096-3101. 10.1021/es702789k.

Tao, Lin, Jing Ma, Tatsuya Kunisue, E. Laurence Libelo, Shinsuke Tanabe, and Kurunthachalam Kannan. 2008. "Perfluorinated Compounds in Human Breast Milk from Several Asian Countries, and in Infant Formula and Dairy Milk from the United States." Environmental Science & Technology 42 (22):8597-8602. 10.1021/es801875v.

Tao, Yousheng, Hirofumi Kanoh, Lloyd Abrams, and Katsumi Kaneko. 2006. "Mesopore-Modified Zeolites: Preparation, Characterization, and Applications." Chemical Reviews 106 (3):896-910. 10.1021/cr040204o.

Tartu, Sabrina, Jon Aars, Magnus Andersen, Anuschka Polder, Sophie Bourgeon, Benjamin Merkel, Andrew D. Lowther, Jenny Bytingsvik, Jeffrey M. Welker, Andrew E. Derocher, Bjørn Munro Jenssen, and Heli Routti. 2018. "Choose Your Poison—Space-Use Strategy Influences Pollutant Exposure in Barents Sea Polar Bears." Environmental Science & Technology. 10.1021/acs.est.7b06137.

Tartu, Sabrina, Geir W. Gabrielsen, Pierre Blévin, Hugh Ellis, Jan Ove Bustnes, Dorte Herzke, and Olivier Chastel. 2014. "Endocrine and Fitness Correlates of Long-Chain Perfluorinated Carboxylates Exposure in Arctic Breeding Black-Legged Kittiwakes." Environmental Science & Technology 48 (22):13504-13510. https://doi.org/10.1021/es503297n.

Tatum-Gibbs, K., J. F. Wambaugh, K. P. Das, R. D. Zehr, M. J. Strynar, A. B. Lindstrom, A. Delinsky, and C. Lau. 2011. "Comparative pharmacokinetics of perfluorononanoic acid in rat and mouse." Toxicology 281 (1-3):48-55. 10.1016/j.tox.2011.01.003.

Tavasoli, Elham, Jenna L. Luek, James P. Malley, and Paula J. Mouser. 2021. "Distribution and fate of per- and polyfluoroalkyl substances (PFAS) in wastewater treatment facilities." Environmental Science: Processes & Impacts 23 (6):903-913. 10.1039/D1EM00032B.

Taylor, Adam C., Gary R. Fones, Branislav Vrana, and Graham A. Mills. 2021. "Applications for Passive Sampling of Hydrophobic Organic Contaminants in Water—A Review." Critical Reviews in Analytical Chemistry 51 (1):20-54. 10.1080/10408347.2019.1675043.

Taylor, Matthew D., Jennifer Bräunig, Jochen F. Mueller, Marcus Crompton, R. Hugh Dunstan, and Sandra Nilsson. 2019. "Metabolomic profiles associated with exposure to per- and polyfluoroalkyl substances (PFASs) in aquatic environments." Environmental Science: Processes & Impacts 21 (11):1980-1990. 10.1039/C9EM00394K.

Taylor, P. H. 2009. ECA Incineration Testing Program: Laboratory-scale incineration testing of fluoropolymers. U.S. EPA Docket No. OPPT-2003-0071: University of Dayton Research Institute.

Taylor, P. H., T. Yamada, R. C. Striebich, J. L. Graham, and R. J. Giraud. 2014. "Investigation of waste incineration of fluorotelomer-based polymers as a potential source of PFOA in the environment." Chemosphere 110:17-22. https://doi.org/10.1016/j.chemosphere.2014.02.037.

TCEQ. 2016. Perfluoro Compounds (PFCs) Various CASRN Numbers, Revisions.

TCEQ. 2017. Texas Risk Reduction Program. https://www.tceq.texas.gov/remediation/trrp/trrp.html

Teel, Amy, Dennis Finn, Jeremy Schmidt, Lynn Cutler, and Richard Watts. 2007. "Rates of Trace Mineral-Catalyzed Decomposition of Hydrogen Peroxide." Journal of Environmental Engineering 133 (8). https://doi.org/10.1061/(ASCE)0733-9372(2007)133:8(853).

Tennessee Riverkeeper, Inc. 2017. Tennessee Riverkeeper, Inc. v. 3M Co. No. 5:16-cv-01029-AKK, 2017 WL 784991: 2017 N.D. Ala. Feb. 10.

Tenorio, Raul, Jinyong Liu, Xin Xiao, Andrew Maizel, Christopher P. Higgins, Charles E. Schaefer, and Timothy J. Strathmann. 2020. "Destruction of Per- and Polyfluoroalkyl Substances (PFASs) in Aqueous Film-Forming Foam (AFFF) with UV-Sulfite Photoreductive Treatment." Environmental Science & Technology 54 (11):6957-6967. 10.1021/acs.est.0c00961.

Tersus Environmental. 2018. "Chemical Fixation of Organic & Inorganic Contaminants."

Tester, Jefferson W., H. Richard Holgate, Fred J. Armellini, Paul A. Webley, William R. Killilea, Glenn T. Hong, and Herbert E. Barner. 1993. "Supercritical Water Oxidation Technology." In Emerging Technologies in Hazardous Waste Management III, 35-76. Vol. 518, ACS Symposium Series. American Chemical Society. ISBN No. 9780841225305.

Tetra Tech. 2021. Synthetic Turf Laboratory Testing and Analysis Summary Report, Martha's Vineyard Regional High School Athletic Fields Project. DRI 352-M4. Oak Bluffs, MA.

Tetra Tech. 2022. "Final Annual Technical Memorandum for Per and Polyfluoroalkyl Substances, July and October 2019, January and May 2020 Surface Water Sampling and July 2019 Sediment Sampling."

Tetra Tech. 2022. Per- and Polyfluoroalkyl Substances Site Inspection Report for Ames Research Center (Draft). Washington, D.C.: National Aeronautics and Space Administration Headquarters.

Texas Molecular. 2021. "PFAS Disposal Solution for Wastewater, Leachate, Groundwater, and Fire Fighting Water." accessed 2021. https://www.texasmolecular.com/pfas/.

Thackray, Colin, and Noelle Selin. 2017. "Uncertainty and variability in atmospheric formation of PFCAs from fluorotelomer precursors." Atmospheric Chemistry and Physics 17:4585-4597. https://doi.org/10.5194/acp-17-4585-2017.

Thackray, Colin P., Noelle E. Selin, and Cora J. Young. 2020. "A global atmospheric chemistry model for the fate and transport of PFCAs and their precursors." Environmental Science: Processes & Impacts 22 (2):285-293. 10.1039/C9EM00326F.

Thalheimer, A.H., L.B. McConney, I.K. Kalinovich, A.V. Pigott, J.D. Franz, H.T. Holbert, D. Mericas, and Z.J. Puchacz. 2017. Use and Potential Impacts of AFFF Containing PFASs at Airports. No. Project 02-60: Engineering The National Academies of Sciences, and Medicine. https://trid.trb.org/view/1473089.

Thibodeaux, J. R., R. G. Hanson, J. M. Rogers, B. E. Grey, B. D. Barbee, J. H. Richards, J. L. Butenhoff, L. A. Stevenson, and C. Lau. 2003. “Exposure to perfluorooctane sulfonate during pregnancy in rat and mouse. I: maternal and prenatal evaluations.” Toxicol Sci 74 (2):369-81. 10.1093/toxsci/kfg121.

Thoma, Eben D., Robert S. Wright, Ingrid George, Max Krause, Dario Presezzi, Valentino Villa, William Preston, Parik Deshmukh, Phil Kauppi, and Peter G. Zemek. 2022. “Pyrolysis processing of PFAS-impacted biosolids, a pilot study.” Journal of the Air & Waste Management Association 72 (4):309-318. 10.1080/10962247.2021.2009935.

Thomas, Ryan, Kristen Jenkins, Beth Landale, Grant Trigger, Thomas M. Holsen, Sophia Dore, Donald Pope, and Jennifer Wasielewski. 2020. “Evaluation of PFAS treatment technology: Alkaline ozonation.” Remediation Journal 30 (3):27-37. https://doi.org/10.1002/rem.21654.

Thomford, P. 2002. 104-week dietary chronic toxicity and carcinogenicity study with perfluorooctane sulfonic acid potassium salt (PFOS; T-6295) in rats. 6329-183: Covance Laboratories Inc.

Thompson, A., and K.W. Goyne. 2012. “Introduction to the Sorption of Chemical Constituents in Soils.” Nature Education Knowledge 4 (4):7. https://www.nature.com/scitable/knowledge/library/introduction-to-the-sorption-of-chemical-constituents-94841002.

Thompson, Jack, Geoff Eaglesham, Julien Reungoat, Yvan Poussade, Michael Bartkow, Michael Lawrence, and Jochen F. Mueller. 2011. “Removal of PFOS, PFOA and other perfluoroalkyl acids at water reclamation plants in South East Queensland Australia.” Chemosphere 82 (1):9-17. https://doi.org/10.1016/j.chemosphere.2010.10.040.

Thompson, Jake T., Nicole M. Robey, Thabet M. Tolaymat, John A. Bowden, Helena M. Solo-Gabriele, and Timothy G. Townsend. 2023. “Underestimation of Per- and Polyfluoroalkyl Substances in Biosolids: Precursor Transformation During Conventional Treatment.” Environmental Science & Technology 57 (9):3825-3832. https://doi.org/10.1021/acs.est.2c06189.

Thompson, Kyle A., Soroosh Mortazavian, Dana J. Gonzalez, Charles Bott, Jennifer Hooper, Charles E. Schaefer, and Eric R. V. Dickenson. 2022. “Poly- and Perfluoroalkyl Substances in Municipal Wastewater Treatment Plants in the United States: Seasonal Patterns and Meta-Analysis of Long-Term Trends and Average Concentrations.” ACS ES&T Water 2 (5):690-700. 10.1021/acsestwater.1c00377.

Thomsen, C., L. S. Haug, H. Stigum, M. Froshaug, S. L. Broadwell, and G. Becher. 2010. “Changes in concentrations of perfluorinated compounds, polybrominated diphenyl ethers, and polychlorinated biphenyls in Norwegian breast-milk during twelve months of lactation.” Environ Sci Technol 44 (24):9550-6. 10.1021/es1021922.

Thoreson, K. 2017. PlumeStop Technology with an Overview on In Situ Containment of Perfluorinated Chemicals (PFAS and PFOA). Webinar presented February 16, 2017.

Tian, Ying, Yiming Yao, Shuai Chang, Zhen Zhao, Yangyang Zhao, Xiaojia Yuan, Fengchang Wu, and Hongwen Sun. 2018. “Occurrence and Phase Distribution of Neutral and Ionizable Per- and Polyfluoroalkyl Substances (PFASs) in the Atmosphere and Plant Leaves around Landfills: A Case Study in Tianjin, China.” Environmental Science & Technology 52 (3):1301-1310. https://doi.org/10.1021/acs.est.7b05385.

Tickner, J. 2022. Advancing Safer Alternatives to AFFF: Lessons Learned From a SERDP Funded-Initiative. SERDP Project WP19-1424: SERDP-ESTCP. https://www.serdp-estcp.org/projects/details/da4a70e8-393f-493b-98b9-93ac1f3ad2af.

Tidwell, Lane G., Sarah E. Allan, Steven G. O’Connell, Kevin A. Hobbie, Brian W. Smith, and Kim A. Anderson. 2016. “PAH and OPAH Flux during the Deepwater Horizon Incident.” Environmental Science & Technology 50 (14):7489-7497. 10.1021/acs.est.6b02784.

Titaley, Ivan A., Florentino B. De la Cruz, and Jennifer A. Field. 2020. “Comment on “Release of Volatile Per- and Polyfluoroalkyl Substances from Aqueous Film-Forming Foam”.” Environmental Science & Technology Letters 7 (11):866-868. https://doi.org/10.1021/acs.estlett.0c00591.

Titaley, Ivan A., Jared Khattak, Jialin Dong, Christopher I. Olivares, Bill DiGuiseppi, Christopher C. Lutes, and Jennifer A. Field. 2022. "Neutral Per- and Polyfluoroalkyl Substances, Butyl Carbitol, and Organic Corrosion Inhibitors in Aqueous Film-Forming Foams: Implications for Vapor Intrusion and the Environment." Environmental Science & Technology 56 (15):10785-10797. 10.1021/acs.est.2c02349.

Tokranov, Andrea K., Denis R. LeBlanc, Heidi M. Pickard, Bridger J. Ruyle, Larry B. Barber, Robert B. Hull, Elsie M. Sunderland, and Chad D. Vecitis. 2021. "Surface-water/groundwater boundaries affect seasonal PFAS concentrations and PFAA precursor transformations." Environmental Science: Processes & Impacts. https://doi.org/10.1039/D1EM00329A.

Tokranov, Andrea K., Denis R. LeBlanc, Heidi M. Pickard, Bridger J. Ruyle, Larry B. Barber, Robert B. Hull, Elsie M. Sunderland, and Chad D. Vecitis. 2021. "Surface-water/groundwater boundaries affect seasonal PFAS concentrations and PFAA precursor transformations." Environmental Science: Processes & Impacts 23 (12):1893-1905. 10.1039/D1EM00329A.

Tominaga, Nobuaki, Shinya Kohra, Taisen Iguchi, and Koji Arizono. 2004. "Effects of Perfluoro Organic Compound Toxicity on Nematode Caenorhabditis elegans Fecundity." Journal of Health Science 50 (5):545-550. https://doi.org/10.1248/jhs.50.545.

Tomy, Gregg T., Wes Budakowski, Thor Halldorson, Paul A. Helm, Gary A. Stern, Ken Friesen, Karen Pepper, Sheryl A. Tittlemier, and Aaron T. Fisk. 2004. "Fluorinated Organic Compounds in an Eastern Arctic Marine Food Web." Environmental Science & Technology 38 (24):6475-6481. 10.1021/es049620g.

Tomy, Gregg T., Kerri Pleskach, Steve H. Ferguson, Jonathon Hare, Gary Stern, Gordia MacInnis, Chris H. Marvin, and Lisa Loseto. 2009. "Trophodynamics of Some PFCs and BFRs in a Western Canadian Arctic Marine Food Web." Environmental Science & Technology 43 (11):4076-4081. 10.1021/es900162n.

Tow, Emily W., Mahmut Selim Ersan, Soyoon Kum, Tae Lee, Thomas F. Speth, Christine Owen, Christopher Bellona, Mallikarjuna N. Nadagouda, Anne M. Mikelonis, Paul Westerhoff, Chandra Mysore, Val S. Frenkel, Viraj deSilva, W. Shane Walker, Andrew K. Safulko, and David A. Ladner. 2021. "Managing and treating per- and polyfluoroalkyl substances (PFAS) in membrane concentrates." AWWA Water Science 3 (5):e1233. https://doi.org/10.1002/aws2.1233.

Town of Harvard MA. 2020. Policy 1-2020: Well water quality testing for property sales and new construction. Harvard, MA: Office of the Board of Health. https://www.harvard-ma.gov/sites/g/files/vyhlif676/f/uploads/water_quality_policy_for_pfas_090820.pdf.

Transport Canada. 2017. Per- and Polyfluoroalkyl Substances (PFAS) Field Sampling Guidance.

Trautmann, A. M., H. Schell, K. R. Schmidt, K-M. Mangold, and A. Tiehm. 2015. "Electrochemical degradation of perfluoroalkyl and polyfluoroalkyl substances (PFASs) in groundwater." Water Science & Technology 71 (10):1569-1575. https://doi.org/10.2166/wst.2015.143.

Trier, Xenia, Kit Granby, and Jan Christensen. 2011. "Polyfluorinated surfactants (PFS) in paper and board coatings for food packaging." Environmental Science and Pollution Research 18:1108-1120. https://doi.org/10.1007/s11356-010-0439-3.

Trihydro. 2019. Final Conceptual Site Model Report for Ellsworth Air Force Base, South Dakota.

Trihydro. 2021. "Project Overview: Using Environmental Sequence Stratigraphy to Build More Accurate Conceptual Site Models." accessed 2023. https://www.trihydro.com/projects/project-details/using-environmental-sequence-stratigraphy-to-build-more-accurate-conceptual-site-models-for-3-air-force-installations.

Trudel, David, Lea Horowitz, Matthias Wormuth, Martin Scheringer, Ian T. Cousins, and Konrad Hungerbühler. 2008. "Estimating Consumer Exposure to PFOS and PFOA." Risk Analysis 28 (2):251-269. 10.1111/j.1539-6924.2008.01017.x.

Trumpey, A.J., D. Daigel, and G. Nowak. 2019. "Communicating During an Outbreak of Public Health Investigation." In The CDC Field Epidemiology Manual, Fourth Edition, edited by S.A. Rasmussen and R.A. Goodman. ISBN No.

978-0190624248.

Tsai, Yu-Ting, Angela Yu-Chen Lin, Yu-Hsiang Weng, and Kung-Cheh Li. 2010. "Treatment of Perfluorinated Chemicals by Electro-Microfiltration." Environmental Science & Technology 44 (20):7914-7920. https://doi.org/10.1021/es101964y.

Tsang, W., D. R. Burgess, and V. Babushok. 1998. "On the Incinerability of Highly Fluorinated Organic Compounds." Combustion Science and Technology 139 (1):385-402. https://doi.org/10.1080/00102209808952095.

Tseng, N. 2012. "Feasibility of Biodegradation of Polyfluoroalkyl and Perfluoroalkyl Substances." Civil Engineering, UCLA.

Tseng, Nancy, Ning Wang, Bogdan Szostek, and Shaily Mahendra. 2014. "Biotransformation of 6:2 Fluorotelomer Alcohol (6:2 FTOH) by a Wood-Rotting Fungus." Environmental Science & Technology 48 (7):4012-4020. https://doi.org/10.1021/es4057483.

Tu, Wenqing, Rubén Martínez, Laia Navarro-Martin, Daniel J. Kostyniuk, Christine Hum, Jing Huang, Mi Deng, Yuanxiang Jin, Hing Man Chan, and Jan Alexander Mennigen. 2019. "Bioconcentration and Metabolic Effects of Emerging PFOS Alternatives in Developing Zebrafish." Environmental Science & Technology 53 (22):13427-13439. 10.1021/acs.est.9b03820.

TURI. 2020. Per- and Polyfluoroalkyl Substances (PFAS) in Artificial Turf Carpet Fact Sheet. University of Massachusetts Toxics Use Reduction Institute, Lowell. https://www.turi.org/content/download/12963/201149/file/TURI+fact+sheet+-+PFAS+in+artificial+turf.pdf.

TURI. 2023. Guidance for Reporting Per- and Poly-Fluoroalkyl Substances (PFAS) under the Toxics Use Reduction Act (TURA), including Individually Listed PFAS and the Certain PFAS Not Otherwise Listed (NOL) Category. https://www.turi.org/content/download/13942/220270/file/Guidance+for+Reporting+of+PFAS+under+TURA+March+2023.pdf.

U.S. Air Force. 2017. "DoD 2017.B STTR Solicitation AFFF Disposal." https://www.sbir.gov/sbirsearch/detail/1254657.

USDOD. 2021. DoD 2021 memo requiring use of EPA Method 1633 for media other than drinking water. https://denix.osd.mil/dod-pfas/osd-policies/documents/pfas-in-media/.

UK Environment Agency. 2004. Environmental Risk Evaluation Report: Perfluorooctanesulfonate (PFOS). United Kingdom: Research Contractor: Building Research Establishment Ltd. and Risk and Policy Analysts Ltd.

Ulhaq, Mazhar, Gunnar Carlsson, Stefan Örn, and Leif Norrgren. 2013. "Comparison of developmental toxicity of seven perfluoroalkyl acids to zebrafish embryos." Environmental Toxicology and Pharmacology 36 (2):423-426. https://doi.org/10.1016/j.etap.2013.05.004.

UNEP. 2008. Report of the Persistent Organic Pollutants Review Committee on the work of its fourth meeting – Addendum to the risk management evaluation for perfluorooctane sulfonate. http://chm.pops.int/Portals/0/download.aspx?d=UNEP-POPS-POPRC.4-15-Add.6.English.pdf

UNEP. 2009. SC-4/17: Listing of perfluorooctane sulfonic acid, its salts and perfluorooctane sulfonyl fluoride. http://chm.pops.int/Portals/0/download.aspx?d=UNEP-POPS-COP.7-SC-7-2.English.pdf

UNEP. 2011. Report of the Persistent Organic Pollutants Review Committee on the work of its sixth meeting, Addendum, Guidance on alternatives to perfluorooctane sulfonic acid and its derivatives. UNEP/POPS/POPRC.6/13/Add.3/Rev: UNEP. https://chm.pops.int/Portals/0/download.aspx?d=UNEP-POPS-POPRC.6-13-Add.3-Rev.1.English.pdf

UNEP. 2019. UNEP/POPS/COP.9/30: Report of the Conference of the Parties to the Stockholm Convention on Persistent Organic Pollutants on the work of its ninth meeting. http://www.pops.int.

UNEP. 2019. UNEP/POPS/POPRC.15/7: Report of the Persistent Organic Pollutants Review Committee on the work of its fifteenth meeting. http://www.pops.int.

University of Connecticut. 2022. UCONN Senior Design Project (2021-2022) Laboratory Analysis of PFAS in Turf Leachates.

University of Florida. 2018. Provisional irrigation water risk-based screening levels for PFOS and PFOA.

https://floridadep.gov/sites/default/files/Prov_Irrigation_Water_Risk-Based_Screen_Lvls_PFOA_PFOS_25Jul18.pdf.

Urtiaga, A., C. Fernandez-Gonzalez, S. Gomez-Lavin, and I. Ortiz. 2015. “Kinetics of the electrochemical mineralization of perfluorooctanoic acid on ultrananocrystalline boron doped conductive diamond electrodes.” Chemosphere 129:20-6. https://doi.org/10.1016/j.chemosphere.2014.05.090.

US DOE. 2020. “Glossary of Environmental Restoration Terms. The Risk Assessment Information System.” https://rais.ornl.gov/home/glossary.html#E.

US Naval Research Laboratory. 2017. “Aqueous Film-Forming Foam.”

USACE. 2018. Containment and Disposal of Aqueous Film-Forming Foam Solution Guidance. ETL-1110-3-4810003.

USDOD. 1997. Containment and Disposal of Aqueous Film Forming Foam Solution.

USDOD. 2009. Emerging Contaminants, June 2009. http://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/471518p.pdf.

USDOD. 2014. Chemical & Material Emerging Risk Alert; Aqueous Film Forming Foam (AFFF), Risk Alert 03-11. https://www.denix.osd.mil/cmrmp/ecmr/ecprogrambasics/.

USDOD. 2014. Memorandum for Deputy Chief of Naval Operations (Fleet Readiness and Logistics) (N4) Deputy Commandant Of The Marine Corps (Installations and Logistics). Subject: Perfluorinated Compounds (PFCs)- An Emerging Environmental Issue. http://www.secnav.navy.mil/eie/Documents/Perfluorinated-Compounds-(PFCs)-An-Emerging-Environmental-Issue.pdf.

USDOD. 2017. Performance Specification: Fire Extinguishing Agent, Aqueous Film-Forming Foam (AFFF) Liquid Concentrate, for Fresh and Sea Water. http://quicksearch.dla.mil/Transient/D4B6D2C750CA42EBA876A8BCDCAD51AA.pdf

USDOD. 2017. Aqueous Film Forming Foam Report to Congress. https://www.denix.osd.mil/derp/home/documents/aqueous-film-forming-foam-report-to-congress/Aqueous%20Film%20Forming%20Foam%20(AFFF)%20Report%20to%20Congress_DENIX.PDF.

USDOD. 2018. Qualified Products Database: “Performance Specification: Fire Extinguishing Agent, Aqueous Film-Forming Foam (AFFF) Liquid Concentrate, for Fresh and Sea Water. MIL-PRF-24385F(SH). http://quicksearch.dla.mil/qsDocDetails.aspx?ident_number=94307.

USDOD. 2018. General Data Validation Guidelines. https://denix.osd.mil/edqw/documents/documents/general-data-validation-guidelines-final/.

USDOD. 2018. Department of Defense Alternatives to Aqueous Film Forming Foam – Report to Congress. https://denix.osd.mil/derp/home/documents/alternatives-to-aqueous-film-forming-foam-report-to-congress/.

USDOD. 2018. Army Guidance for Addressing Releases of Per- and Polyfluoroalkyl Substances (PFAS). U.S. Army U.S. Department of Defense. www.fedcenter.gov.

USDOD. 2019. Department of Defense/Department of Energy Consolidated Quality Systems Manual for Environmental Laboratories Version 5.3. DoD Environmental Data Quality Workgroup and DOE Consolidated Audit Program (DOECAP). https://denix.osd.mil/edqw/documents/manuals/qsm-version-5-3-final/.

USDOD. 2020. Module 3: Data Validation Procedure for Per- and Polyfluoroalkyl Substances Analysis by Quality Systems Manual for Environmental Laboratories (QSM) Table B-15. Department of Defense/Department of Energy. https://denix.osd.mil/edqw/documents/documents/module-3-data-validation/.

USDOD. 2020. Interim Per- and Polyfluoroalkyl Substances (PFAS) Site Guidance for NAVFAC Remedial Project Managers (RPMs). Naval Facilities Engineering Command (NAVFAC) U.S. Department of Defense.

USDOD. 2020. Air Force Guidance Memorandum Establishing Aqueous Film Forming Foam (AFFF)-Related Waste Management Implementation Guidance. AFGM-2019-32-02: U.S. Air Force U.S. Department of Defense.

USDOD. 2021. Module 3: Data Validation Procedure for Per- and Polyfluoroalkyl Substances Analysis by Quality Systems Manual for Environmental Laboratories (QSM) Table B-15. Version 5.4: Department of Defense/Department of Energy. https://denix.osd.mil/edqw/.

USDOD. 2022. Memorandum. Temporary Prohibition on Incineration of Materials Containing Per- and Polyfluoroalkyl Substances (PFAS). Washington, DC: U.S. Department of Defense. https://media.defense.gov/2022/Apr/28/2002986273/-1/-1/1/TEMPORARY-PROHIBITION-ON-INC%5b...%5dNG-PRE-AND-POLYFLUOROALKYL-SUBSTANCES-PFAS-APRIL-26-2022.PDF.

USDOD. 2022. Module 6: Data Validation Procedure for Per- and Polyfluoroalkyl Substances Analysis by Quality Systems Manual (QSM) Table B-24. Department of Defense/Department of Energy. Environmental Data Quality Workgroup, October 18, 2022.

USDOD. 2023. Performance Specification. Fire Extinguishing Agent, Fluorine-Free Foam (F3) Liquid Concentrate, For Land-Based, Fresh Water Applications. MIL-PRF-32725. https://media.defense.gov/2023/Jan/12/2003144157/-1/-1/1/MILITARY-SPECIFICATION-FOR-FIRE-EXTINGUISHING-AGENT-FLUORINE-FREE-FOAM-F3-LIQUID-CONCENTRATE-FOR-LAND-BASED-FRESH-WATER-APPLICATIONS.PDF.

USDOD. 2023. Interim Guidance on Destruction or Disposal of Materials Containing Per- and Polyfluoroalkyl Substances in the United States. Washington D.C. https://www.acq.osd.mil/eie/eer/ecc/pfas/news.html.

USDOD. 2023. Statement on the Department's PFAS Cleanup Progress. Washington, D.C. https://www.acq.osd.mil/eie/eer/ecc/pfas/news.html.

USDOD EDQW. 2017. Department of Defense (DoD) Quality Systems Manual (QSM) for Environmental Laboratories," Version 5.1. http://www.denix.osd.mil/edqw/home/

USDOD EDQW. 2017. Bottle Selection and other Sampling Considerations When Sampling for Per- and Poly-Fluoroalkyl Substances (PFASs) Revision 1.2. http://www.denix.osd.mil/edqw/home/

USEPA. 1974. "Title XIV of The Public Health Service Act: Safety of Public Water Systems (Safe Drinking Water Act)."

USEPA. 1985. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. PB-85-227049. Washington, D.C.: US EPA ORD. https://www.epa.gov/sites/production/files/2016-02/documents/guidelines-water-quality-criteria.pdf.

USEPA. 1986. Method 0010 Modified Method 5 Sampling Train. https://www.epa.gov/sites/production/files/2015-12/documents/0010.pdf.

USEPA. 1986. Guidelines for the Health Risk Assessment of Chemical Mixtures. EPA/630/R-98/002. Washington, D.C. https://www.epa.gov/sites/default/files/2014-11/documents/chem_mix_1986.pdf.

USEPA. 1986. Permit Guidance Manual on Unsaturated Zone Monitoring for Hazardous Waste Land Treatment Units. EPA/530-SW-86-040. Washington, DC.

USEPA. 1987. Compendium of Superfund Field Operations Methods. EPA 540/P-87/001a OSWER 9355.0-14.

USEPA. 1988. CERCLA Compliance and Other Laws Manual: Interim Final. EPA/540/G-89/006.

USEPA. 1988. Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA. EPA/540/G-89/004, OSWER Directive 9355.3-01.

USEPA. 1988. Determination of MCLGs and MCLs. WSG H15: National Service Center for Environmental Publications. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100NBDX.TXT

USEPA. 1989. RCRA Facility Investigation Guidance. EPA 53/SW-89-031.

USEPA. 1989. Risk Assessment Guidance for Superfund Volume I Human Health Evaluation Manual (Part A). Interim Final. EPA/540/1-89/002: US Environmental Protection Agency. https://www.epa.gov/sites/production/files/2015-09/documents/rags_a.pdf.

USEPA. 1989. Water Quality Criteria to Protect Wildlife Resources. EPA/600/3-89/067 PB 89 220016. Corvallis, OR. https://nepis.epa.gov/EPA/html/Pubs/pubalpha_W.html.

USEPA. 1990. Engineering Bulletin: Soil Washing Treatment. EPA540/2-90-017. Washington, DC.

USEPA. 1991. ARARs Q's and A's: General Policy, RCRA, CWA, SDWA, Post-ROD Information, and Contingent Waivers. OSWER Publication 9234.2-01/FS-A. https://semspub.epa.gov/work/HQ/174497.pdf

USEPA. 1991. Risk Assessment Guidance for Superfund: Volume 1- Human Health Evaluation Manual (Part B, Development of Risk-based Preliminary Remediation Goals). EP A/540/R-92/003: Interim Office of Emergency and Remedial Response.

USEPA. 1992. Framework for Ecological Risk Assessment. EPA/630/R-92/001. Washington, DC: Risk Assessment Forum US Environmental Protection Agency.

USEPA. 1993. Use of IRIS Values in Superfund Risk Assessment. OSWER Directive 9285.7-16. Washington, DC: US EPA.

USEPA. 1993. Wildlife Exposure Factors Handbook. USEPA/600/R-93/187: USEPA. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=2799.

USEPA. 1993. Innovative Site Remediation Technology Soil Washing/Soil Flushing Volume 3. EPA542/B93/012. Washington, DC.

USEPA. 1995. Final Water Quality Guidance for the Great Lakes System. 60 FR 1536.

USEPA. 1995. Great Lakes Water Quality Initiative Technical Support Document for Wildlife Criteria. EPA-820-B-95-009. Washington, DC: Office of Water US EPA. https://tinyurl.com/chptntfc.

USEPA. 1995. Great Lakes Water Quality Initiative Criteria Documents for the Protection of Wildlife: DDT, Mercury, 2,3,7,8-TCDD, PCBs. EPA/820/B-95/008. Washington, DC: Office of Water US EPA. https://tinyurl.com/jje955df.

USEPA. 1995. User's Guide for the Industrial Source Complex (ISC3) Dispersion Models, Volume II – Description of Model Algorithms. EPA-454/B-95-003b. Research Triangle Park, North Carolina: USEPA. https://gaftp.epa.gov/Air/aqmg/SCRAM/models/other/isc3/isc3v2.pdf.

USEPA. 1996. Emission Factor Documentation for AP-42. Emission Factor and Inventory Group Office of Air Planning and Standards, Section 12.20.

USEPA. 1996. Method 3542 Extraction of Semivolatile Analytes collected using Method 0010 (Modified Method 5 Sampling Train). https://www.epa.gov/sites/production/files/2015-12/documents/3542.pdf.

USEPA. 1996. A Citizen's Guide to Soil Washing. EPA 542-F-96-002. Washington, D.C.: USEPA OSWER (5102G).

USEPA. 1997. Clarification of the Role of Applicable, or Relevant and Appropriate Requirements in Establishing Preliminary Remedial Goals under CERCLA. OSWER Memorandum 9200.4-23.

USEPA. 1997. High Voltage Electron Beam Technology: High Voltage Environmental Applications, Inc. Demonstration Bulletin, Superfund Innovative Technology Evaluation. EPA/540/MR-96/504: US EPA.

USEPA. 1997. Best Management Practices for Soils Treatment Technologies. EPA530/R97/007. Washington, DC.

USEPA. 1998. Hard Chrome Fume Suppressants and Control Technologies. EPA/625/R-98/002: National Risk Management Research Laboratory Center for Environmental Research Information, Office of Research and Development.

USEPA. 1998. Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water. EPA/600/R-98/128.

USEPA. 1999. Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites. OSWER Directive 9200.4-17P.

USEPA. 1999. Physical Separation (Soil Washing) for Volume Reduction of Contaminated Soils and Sediments Processes and Equipment. EPA905/R99/006. Washington, DC.

USEPA. 2000. EPA and 3M Announce Phaseout of PFOS. News Release. May 16, 2000.

USEPA. 2000. Data Quality Objectives Process for Hazardous Waste Site Investigations. EPA QA/G-4HW Final. EPA/600/R-00/007: USEPA.

USEPA. 2000. Perfluorooctyl Sulfonates: Proposed Significant New Use Rule. 65 Federal Register 62319.

USEPA. 2000. Risk Characterization: Science Policy Handbook. EPA 100-B-00-002.

USEPA. 2000. Methodology for Deriving Ambient Water Quality Criteria for the Protection of Human Health. EPA-822-B-00-004. Washington, DC: Office of Water U.S. Environmental Protection Agency, Office of Science and Technology. https://www.epa.gov/sites/production/files/2018-10/documents/methodology-wqc-protection-hh-2000.pdf.

USEPA. 2000. Science Policy Council Handbook, Risk Characterization. EPA 100-B-00-002. Washington, D.C.: Office of Research and Development U.S. Environmental Protection Agency. https://www.epa.gov/risk/risk-management#self.

USEPA. 2000. Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2015-06/documents/volume1.pdf.

USEPA. 2000. Supplementary Guidance for Conducting Health Risk Assessment of Chemical Mixtures. EPA/630/R-00/002. Washington, D.C.: USEPA. https://ofmpub.epa.gov/eims/eimscomm.getfile?p_download_id=4486

USEPA. 2001. Class I Underground Injection Control Program: Study of the Risks Associated with Class I Underground Injection Wells. Washington, D.C.

USEPA. 2002. National Recommended Water Quality Criteria: 2002. EPA-822-R-02-047. Washington, D.C.: U.S. Environmental Protection Agency Office of Water (4304T). https://www.epa.gov/sites/default/files/2018-12/documents/national-recommended-hh-criteria-2002.pdf.

USEPA. 2003. Human Health Toxicity Values in Superfund Risk Assessments. OSWER Directive 9285.7-53.

USEPA. 2003. Perfluorooctanoic Acid (PFOA), Fluorinated Telomers; Request for Comment, Solicitation of Interested Parties for Enforceable Consent Agreement Development, and Notice of Public Meeting. 68 Federal Register 18626. Washington D.C.: USEPA.

USEPA. 2003. Framework for Cumulative Risk Assessment. EPA/600/P-02/001F. Washington, D.C.: Office of Research and Development U.S. Environmental Protection Agency, Center for Public Health and Environmental Assessment (CPHEA), formerly known as the National Center for Environmental Assessment (NCEA). https://www.epa.gov/risk/framework-cumulative-risk-assessment.

USEPA. 2003. Methodology for Deriving Ambient Water Quality Criteria for the Protection of Human Health (2000). Technical Support Document Volume 2: Development of National Bioaccumulation Factors. Washington, DC: U.S. Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPDF.cgi/P1005EZQ.PDF?Dockey=P1005EZQ.PDF.

USEPA. 2003. AERMOD Deposition Algorithms – Science Document (Revised Draft). Research Triangle Park, North Carolina USEPA. https://gaftp.epa.gov/Air/aqmg/SCRAM/models/preferred/aermod/aer_scid.pdf.

USEPA. 2004. An Examination of EPA Risk Assessment Principles and Practices. EPA/100/B-04/001. Washington DC: Office of the Science Advisor.

USEPA. 2004. Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment). Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2015-09/documents/part_e_final_revision_10-03-07.pdf.

USEPA. 2005. Superfund Community Involvement Handbook. EPA 540-K-05-003: Office of Emergency and Remedial Response.

USEPA. 2005. Guidelines for Carcinogen Risk Assessment. EPA/630.P-03/001F. Washington, DC: Risk Assessment Forum US EPA.

USEPA. 2005. Science Advisory Board Consultation Document. Proposed Revisions to Aquatic Life Guidelines. Tissue-

Based Criteria for “Bioaccumulative” Chemicals. Prepared by the Tissue-based Criteria Subcommittee.

USEPA. 2006. 2010/2015 PFOA Stewardship Program. EPA-HQ-2003-0012-1071.

USEPA. 2006. “Risk Management for Per- and Polyfluoroalkyl Substances (PFAS) under TSCA, PFOA Stewardship Program.” Last Modified July 1, 2021. accessed 2021. https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-management-and-polyfluoroalkyl-substances-pfass#tab-3

USEPA. 2006. Guidance on Systematic Planning Using the Data Quality Objectives Process. EPA QA/G-4. EPA/240/B-06/001.

USEPA. 2007. Perfluoroalkyl Sulfonates; Significant New Use Rule. 72 Federal Register 57222. Washington D.C.

USEPA. 2007. Risk Communication in Action: The Risk Communication Workbook. EPA/625/R-05/003: National Risk Management Research Laboratory Office of Research and Development.

USEPA. 2007. Communicating Radiation Risks. EPA-402-F-07-008. Washington, D.C.: Office of Radiation and Indoor Air US Environmental Protection Agency. https://go.usa.gov/xnM8X.

USEPA. 2008. Clean Diesel Technologies and Alternative Fuels. San Francisco, CA: U.S. Environmental Protection Agency Region 9.

USEPA. 2008. Green Remediation: Best Management Practices for Excavation and Surface Restoration. EPA 542-F-08-012: Office of Superfund and Remediation and Technology Innovation.

USEPA. 2008. Drinking Water Contaminant Candidate List 3—Draft. Washington, D.C. https://www.govinfo.gov/content/pkg/FR-2008-02-21/pdf/E8-3114.pdf.

USEPA. 2008. White Paper, Aquatic Life Criteria for Contaminants of Emerging Concern, Part I, General Challenges and Recommendations. Office of Water/Office of Research and Development Emerging Contaminants Workgroup US EPA.

USEPA. 2009. Determination of Selected Perfluorinated Alkyl Acids in Drinking Water by Solid Phase Extraction and Liquid Chromatography/Tandem Mass Spectrometry (LC/MS/MS). USEPA Method 537, Rev 1.1, EPA 600-R-08-092: USEPA.

USEPA. 2009. Long-Chain Perfluorinated Chemicals (PFCs), Action Plan. USEPA. https://www.epa.gov/sites/production/files/2016-01/documents/pfcs_action_plan1230_09.pdf.

USEPA. 2009. PFOS Chromium Electroplater Study. Chicago, IL: US EPA – Region 5. https://www.in.gov/idem/ctap/files/plating_chromium_pfos_study.pdf

USEPA. 2009. Provisional Health Advisories for Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonate (PFOS). USEPA. https://www.epa.gov/sites/production/files/2015-09/documents/pfoa-pfos-provisional.pdf

USEPA. 2009. Washington Works Facility Order on Consent under SDWA Section 1431. USEPA.

USEPA. 2009. Perfluorocarboxylic acid content in 116 Articles of Commerce. EPA/600/R-09/033. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=206124

USEPA. 2009. Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities – Unified Guidance. EPA/530/R-09/007.

USEPA. 2009. Drinking Water Contaminant Candidate List 3—Final. 74 Federal Register 51850. Washington, D.C.: U.S. Environmental Protection Agency. https://www.govinfo.gov/content/pkg/FR-2009-10-08/pdf/E9-24287.pdf.

USEPA. 2010. Superfund Green Remediation Strategy. Washington, DC: Office of Solid Waste and Emergency Response and Office of Superfund Remediation and Technology Innovation USEPA.

USEPA. 2010. Guidance for Implementing the January 2001 Methylmercury Water Quality Criterion. EPA 823-R-10-001. Washington, DC: Office of Water US EPA.

USEPA. 2010. NPDES Permit Writers' Manual. Chapter 5. Technology-Based Effluent Limitations. EPA-833-K-10-001: Office of Water U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-09/documents/pwm_chapt_05.pdf.

USEPA. 2010. NPDES Permit Writers' Manual. Chapter 6. Water Quality-Based Effluent Limitations. EPA-833-K-10-001: Office of Water U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-09/documents/pwm_chapt_06.pdf.

USEPA. 2011. Exposure Factors Handbook 2011 Edition (Final). EPA/600/R-09/052F. Washington, D. C.: U.S. Environmental Protection Agency. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252.

USEPA. 2011. Recommended Use of Body Weight 3/4 as the Default Method in Derivation of the Oral Reference Dose. EPA/100/R11/0001: U. S. Environmental Protection Agency.

USEPA. 2011. Design for the Environment Program Alternatives Assessment Criteria for Hazard Evaluation. Version 2.0. Washington, DC: USEPA Office of Pollution Prevention & Toxics. https://www.epa.gov/sites/default/files/2014-01/documents/aa_criteria_v2.pdf.

USEPA. 2012. A Framework for Sustainability Indicators at EPA. Washington, DC: Office of Research and Development USEPA National Risk Management Research Laboratory.

USEPA. 2012. Methodology for Understanding and Reducing a Project's Environmental Footprint. Office of Solid Waste and Emergency Response and Office of Superfund Remediation and Technology Innovation.

USEPA. 2012. Green Remediation Best Management Practices: Implementing In Situ Thermal Technologies. EPA 542-F-12-029: Office of Superfund and Remediation and Technology Innovation.

USEPA. 2012. National Emissions Standards for Hazardous Air Pollutant Emissions: Hard and Decorative Chromium Electroplating and Chromium Anodizing Tanks; and Steel Pickling – HCl Process Facilities and Hydrochloric Acid Regeneration Plant. 77 Federal Register 58219. Washington D.C.

USEPA. 2012. Benchmark Dose Technical Guidance. EPA/100/R-12/001.

USEPA. 2012. A Citizen's Guide to Incineration. EPA 542-F-12-010. Washington, D.C.: USEPA OSWER (5102G). https://www.epa.gov/sites/default/files/2015-04/documents/a_citizens_guide_to_incineration.pdf.

USEPA. 2013. Porewater Sampling Operating Procedure. SESDPROC-513-R2.

USEPA. 2013. Science and Ecosystem Support Division (SESD) Operating Procedure: Potable Water Supply Sampling. SESDPROC-305-R3.

USEPA. 2013. Green Remediation Best Management Practices: Materials and Waste Management. EPA 542-F-13-003: Office of Superfund and Remediation and Technology Innovation.

USEPA. 2013. Climate Change Adaptation Technical Fact Sheet: Groundwater Remediation Systems. EPA 542-F-13-004: Office of Superfund Remediation and Technology Innovation.

USEPA. 2013. Tier 3 Toxicity Value White Paper. OSWER Directive 9285.7-86: USEPA.

USEPA. 2013. Toxicological Review of 1,4-Dioxane (with Inhalation Update). Washington, D.C.: U.S. Environmental Protection Agency.

USEPA. 2014. Emerging Contaminants Fact Sheet – PFOS and PFOA. EPA 505-F-11-002.

USEPA. 2014. Naval Air Warfare Center Warminster Administrative Order under SDWA Section 1431.

USEPA. 2014. Climate Change Adaptation Plan. 100-K14-001: USEPA.

USEPA. 2014. Climate Change Adaptation Technical Fact Sheet: Landfills and Containment as an Element of Site Remediation. EPA-542-F-14-001: Office of Superfund Remediation and Technology Innovation.

USEPA. 2014. Provisional Peer-Reviewed Toxicity Values for Perfluorobutane Sulfonate (CASRN 375-73-5) and Related

Compound Potassium Perfluorobutane Sulfonate (CASRN 29420-49-3). Cincinnati, OH: Superfund Health Risk Technical Support Center National Center for Environmental Assessment Office of Research and Development U.S. Environmental Protection Agency. https://cfpub.epa.gov/ncea/pprtv/chemicalLanding.cfm?pprtv_sub_id=1843.

USEPA. 2014. National Functional Guidelines for Superfund Organic Methods Data Review. USEPA-540-R-014-002. (OSWER 9335.0-132): Office of Superfund Remediation and Technology Innovation.

USEPA. 2014. Estimated Fish Consumption Rates for the U.S. Population and Selected Subpopulations (NHANES 2003-2010). Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2015-01/documents/fish-consumption-rates-2014.pdf.

USEPA. 2015. Administrative Order for Response Action. Docket No.: SDWA-01-2015-0061: USEPA Region 1. https://semspub.epa.gov/work/01/584719.pdf

USEPA. 2015. Long-Chain Perfluoroalkyl Carboxylate and Perfluoroalkyl Sulfonate Chemical Substances; Significant New Use Rule. 80 Federal Register 2885. Washington D.C.: USEPA.

USEPA. 2015. Proposed Rule: Significant New Use Rules: Long-Chain Perfluoroalkyl Carboxylate and Perfluoroalkyl Sulfonate Chemical Substances. EPA-HQ-OPPT-2013-0225: USEPA. https://www.regulations.gov/document?D=EPA-HQ-OPPT-2013-0225-0001

USEPA. 2015. Risk-Screening Environmental Indicators (RSEI) Model Version 2.3.4. Technical Appendix B Physicochemical Properties for TRI Chemicals and Chemical Categories. Washington, DC: USEPA. https://www.epa.gov/rsei/risk-screening-environmental-indicators-rsei-model-reference-document-history.

USEPA. 2015. Climate Change Adaptation Technical Fact Sheet: Contaminated Sediment Remedies. EPA 542-F-15-009.

USEPA. 2015. Hazardous Waste Cleanup: Chemours Company FC, LLC (Formerly: Dupont Washington Works) in Washington, West Virginia. EPA ID: WVD045875291. https://www.epa.gov/hwcorrectiveactionsites/hazardous-waste-cleanup-chemours-company-fc-llc-formerly-dupont-washington.

USEPA. 2015. Human Health Ambient Water Quality Criteria: 2015 Update. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2015-10/documents/human-health-2015-update-factsheet.pdf.

USEPA. 2015. EPA's Safer Choice Standard. Washington, DC. https://www.epa.gov/sites/default/files/2013-12/documents/standard-for-safer-products.pdf.

USEPA. 2015. Use of Monitored Natural Attenuation for Inorganic Contaminants in Groundwater at Superfund Sites. OSWER Directive 9283.1-36.

USEPA. 2015. Requirements for all Class I wells and class I hazardous waste wells. https://www.epa.gov/sites/default/files/2015-10/documents/page_uic-class1_summary_class1_reqs_508c.pdf.

USEPA. 2016. Definitions. 40 CFR Part 300, Subpart A, Section 300.5. https://www.gpo.gov/fdsys/pkg/CFR-2016-title40-vol30/xml/CFR-2016-title40-vol30-chapI-subchapJ.xml#seqnum300.5.

USEPA. 2016. Drinking Water Health Advisory for Perfluorooctane Sulfonate (PFOS). EPA 822-R-16-004. Washington, DC: Office of Water US EPA, Health and Ecological Criteria Division. https://www.epa.gov/sites/production/files/2016-05/documents/pfos_health_advisory_final_508.pdf

USEPA. 2016. Fact Sheet PFOA and PFOS Drinking Water Health Advisories. EPA800-F-16-003. https://www.epa.gov/sites/production/files/2016-06/documents/drinkingwaterhealthadvisories_pfoa_pfos_updated_5.31.16.pdf

USEPA. 2016. Health Effects Support Document for Perfluorooctane Sulfonate (PFOS). EPA 822-R-16-002: Office of Water US EPA.

USEPA. 2016. Regional Removal Management Levels (RMLs) User's Guide.

https://www.epa.gov/risk/regional-removal-management-levels-rmls-users-guide

USEPA. 2016. High-Resolution Site Characterization (HRSC). https://clu-in.org/characterization/technologies/hrsc/

USEPA. 2016. Memorandum, Consideration of Greener Cleanup Activities in the Superfund Cleanup Process.

USEPA. 2016. Drinking Water Health Advisory for Perfluorooctanoic Acid (PFOA). EPA 822-R-16-005. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2016-05/documents/pfoa_health_advisory_final_508.pdf.

USEPA. 2016. Health Effects Support Document for Perfluorooctanoic Acid (PFOA). EPA 822-R-16-003: Office of Water US EPA. https://www.epa.gov/sites/production/files/2016-05/documents/pfoa_hesd_final_508.pdf

USEPA. 2016. AERMOD Implementation Guide. EPA-454/B-16-013. Research Triangle Park, NC.

USEPA. 2016. The Fourth Unregulated Contaminant Monitoring Rule (UCMR 4). EPA 815-F-16-007: Office of Water (MS-140) US EPA. https://www.epa.gov/sites/production/files/2017-03/documents/ucmr4-fact-sheet-general.pdf.

USEPA. 2016. Aquatic Life Ambient Water Quality Criterion for Selenium – Freshwater 2016. EPA 822-R-16-006. Washington, DC: Office of Water US EPA.

USEPA. 2016. Ecological Effects Tests Guidelines OCSPP 850.1730: Fish Bioconcentration Factor (BCF). EPA 712-C-16-003. Washington, D.C. https://tinyurl.com/EPAEcoEffectsTests.

USEPA. 2017. “Assessing and Managing Chemicals under TSCA.” Last Modified December 18, 2019. accessed 2020. https://www.epa.gov/assessing-and-managing-chemicals-under-tsca

USEPA. 2017. “Basic Information about Per- and Polyfluoroalkyl Substances (PFASs).” https://www.epa.gov/pfas/basic-information-about-and-polyfluoroalkyl-substances-pfass#tab-1.

USEPA. 2017. “Saint-Gobain Performance Plastics, Village of Hoosick Falls, N.Y.”. https://cumulis.epa.gov/supercpad/cursites/csitinfo.cfm?id=0202702.

USEPA. 2017. “EPA History: Resource Conservation and Recovery Act.” https://www.epa.gov/history/epa-history-resource-conservation-and-recovery-act.

USEPA. 2017. EPA’s Non-CBI Summary Tables for 2015 Company Progress Reports (Final Progress Reports). https://www.epa.gov/sites/production/files/2017-02/documents/2016_pfoa_stewardship_summary_table_0.pdf

USEPA. 2017. “Monitoring Unregulated Drinking Water Contaminants Occurrence Data for the Unregulated Contaminant Monitoring Rule.” https://www.epa.gov/dwucmr/occurrence-data-unregulated-contaminant-monitoring-rule

USEPA. 2017. “New Chemicals Program Review of Alternatives for PFOA and Related Chemicals.” https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/new-chemicals-program-review-alternatives-pfoa-and.

USEPA. 2017. “Per- and Polyfluoroalkyl Substances (PFASs) Overview PFAS CLU-IN.org page.” https://clu-in.org/contaminantfocus/default.focus/sec/Per-_and_Polyfluoroalkyl_Substances_(PFASs)/cat/Overview/.

USEPA. 2017. “Per- and Polyfluoroalkyl Substances (PFASs) under TSCA.” https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/and-polyfluoroalkyl-substances-pfass-under-tsca

USEPA. 2017. “Per- and Polyfluoroalkyl Substances (PFASs): What EPA is Doing.”

USEPA. 2017. “Persistent Organic Pollutants: A Global Issue, A Global Response.” https://www.epa.gov/international-cooperation/persistent-organic-pollutants-global-issue-global-response.

USEPA. 2017. “Regional Screening Level (RSL) Calculator.” https://epa-prgs.ornl.gov/cgi-bin/chemicals/csl_search

USEPA. 2017. “Regional Screening Levels (RSLs) – Generic Tables (June 2017).” https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables.

USEPA. 2017. “Research on Per- and Polyfluoroalkyl Substances (PFAS).” https://www.epa.gov/chemical-research/research-and-polyfluoroalkyl-substances-pfas

USEPA. 2017. The Third Unregulated Contaminant Monitoring Rule (UCMR 3): Data Summary, January 2017. https://www.epa.gov/sites/production/files/2017-02/documents/ucmr3-data-summary-january-2017.pdf

USEPA. 2017. Treatment of Perfluorinated Alkyl Substances in Wash Water Using Granular Activated Carbon and Mixed Media.

USEPA. 2017. A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models. EPA/600/R-17/293: USEPA.

USEPA. 2017. Technical Fact Sheet – Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoic Acid (PFOA). EPA 505-F-17-001. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P10141RO.txt.

USEPA. 2017. Best Practices for Environmental Site Management: A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models. EPA/600/R-17/293.

USEPA. 2017. Method 18 – Measurement of Gaseous Organic Compound Emissions by Gas Chromatography. https://www.epa.gov/sites/production/files/2017-08/documents/method_18.pdf.

USEPA. 2017. National Functional Guidelines for Organic Superfund Methods Data Review. OLEM 9355.0-136, EPA-540-R-2017-002. Washington, D.C.: Office of Superfund Remediation and Technology Innovation (OSRTI). https://www.epa.gov/sites/production/files/2017-01/documents/national_functional_guidelines_for_organic_superfund_methods_data_review_013072017.pdf.

USEPA. 2017. Drinking Water Contaminant Candidate List 4—Final Washington, D.C.: U.S. Environmental Protection Agency.

USEPA. 2017. Water Quality Standards Handbook: Chapter 3: Water Quality Criteria. EPA-823-B-17-001. Washington, DC: Office of Science and Technology US EPA Office of Water. https://www.epa.gov/sites/production/files/2014-10/documents/handbook-chapter3.pdf.

USEPA. 2017. Update for Chapter 5 of the Exposure Factors Handbook. Soil and Dust Ingestion. EPA/600/R-17/384F. https://www.epa.gov/sites/default/files/2018-01/documents/efh-chapter05_2017.pdf.

USEPA. 2018. “GenX Chemicals Studies.” Last Modified April 30, 2018. https://www.epa.gov/pfas/genx-chemicals-studies.

USEPA. 2018. “Assessing and Managing Chemicals under TSCA – Fact Sheet: 2010/2015 PFOA Stewardship Program.” Last Modified March 4, 2021. accessed 2021. https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/fact-sheet-20102015-pfoa-stewardship-program#mfg.

USEPA. 2018. “Contaminated Site Clean-up Information: Green Remediation Focus.” USEPA Office of Superfund Remediation and Technology Innovation. accessed 2021. https://clu-in.org/greenremediation/.

USEPA. 2018. Long-Chain Perfluoroalkyl Carboxylate and Perfluoroalkyl Sulfonate Chemical Substances; Significant New Use Rule. Washington, D.C. https://www.reginfo.gov/public/do/eAgendaViewRule?pubId=201810&RIN=2070-AJ99.

USEPA. 2018. DRAFT for Public Comment: Human Health Toxicity Values for Hexafluoropropylene Oxide (HFPO) Dimer Acid and Its Ammonium Salt (CASRN 13252-13-6 and CASRN 62037- 80-3). Also Known as “GenX Chemicals”. EPA Document Number: 823-P-18-001: USEPA Office of Water.

USEPA. 2018. DRAFT for Public Comment: Human Health Toxicity Values for Perfluorobutane Sulfonic Acid (CASRN 375-73-5) and Related Compound Potassium Perfluorobutane Sulfonate (CASRN 29420 49 3). EPA Document Number: 823-R-18-307: USEPA Office of Research and Development.

USEPA. 2018. Final 2016 Effluent Guidelines Program Plan. Washington DC. https://www.epa.gov/sites/production/files/2018-05/documents/final-2016-eg-plan_april-2018.pdf.

USEPA. 2018. “Groundwater and Drinking Water, National Primary Drinking Water Regulations.” accessed 2019.

https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations.

USEPA. 2018. Method 537.1: Determination of Selected Per- and Polyfluorinated Alkyl Substances in Drinking Water by Solid Phase Extraction and Liquid Chromatography/Tandem Mass Spectrometry (LC/MS/MS). Washington, D. C.: Office of Research and Development U.S. Environmental Protection Agency, National Center for Environmental Assessment.

USEPA. 2018. Data Review and Validation Guidelines for Perfluoroalkyl Substances (PFASs) Analyzed Using EPA Method 537. EPA 910-R-18-001. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100VW12.PDF?Dockey=P100VW12.PDF.

USEPA. 2018. “Science Matters: EPA Toxicologists Focus Innovative Research on PFAS Compounds.”. accessed 2020. https://www.epa.gov/sciencematters/epa-toxicologists-focus-innovative-research-pfas-compounds

USEPA. 2018. “EPA Enterprise Vocabulary – Research – Research Resources – Analytical Methods and Protocols.”

USEPA. 2019. PFAS Action Plan. EPA 823R18004. Washington D.C. https://www.epa.gov/sites/default/files/2019-02/documents/pfas_action_plan_021319_508compliant_1.pdf.

USEPA. 2019. “Integrated Risk Information System Glossary.” accessed 2019.

USEPA. 2019. A Message from The IRIS Program. https://www.epa.gov/sites/production/files/2019-04/documents/iris_program_outlook_apr2019.pdf.

USEPA. 2019. “Class I Industrial and Municipal Waste Disposal Wells.”, Accessed June 18, 2019. https://www.epa.gov/uic/class-i-industrial-and-municipal-waste-disposal-wells.

USEPA. 2019. “Requirements for all Class I Wells and Class I Hazardous Waste Wells.” Accessed June 18, 2019. https://www.epa.gov/uic/requirements-all-class-i-wells-and-class-i-hazardous-waste-wells.

USEPA. 2019. “Methodology and Spreadsheets for Environmental Footprint Analysis (SEFA).”, Accessed June 20, 2019. https://clu-in.org/greenremediation/methodology/#SEFA.

USEPA. 2019. Method 533: Determination of Per- and Polyfluoroalkyl Substances in Drinking Water by Isotope Dilution Anion Exchange Solid Phase Extraction and Liquid Chromatography/Tandem Mass Spectrometry. EPA/815-B-19-20. Cincinnati, OH. https://www.epa.gov/sites/production/files/2019-12/documents/method-533-815b19020.pdf.

USEPA. 2019. “Research on Per- and Polyfluoroalkyl Substances (PFAS).” accessed 2020. https://www.epa.gov/chemical-research/research-and-polyfluoroalkyl-substances-pfas.

USEPA. 2019. “Superfund: Applicable or Relevant and Appropriate Requirements (ARARs).” Last Modified 4-4-2019. accessed 2020. https://www.epa.gov/superfund/applicable-or-relevant-and-appropriate-requirements-arars.

USEPA. 2019. Field Equipment Cleaning and Decontamination at the FEC. ASBPROC-206-R4. Athens, GA: Laboratory Services and Applied Science Division USEPA Region 4. https://www.epa.gov/quality/field-equipment-cleaning-and-decontamination-fec.

USEPA. 2019. “Risk Communication.” United States Environmental Protection Agency, Last Modified 11/21/2018, Accessed 2/9/2019. https://www.epa.gov/risk/risk-communication.

USEPA. 2019. “EPA Region 7 Leading Environmentalism and Forwarding Sustainability (L.E.A.F.S.) Awards.” Superfund Redevelopment Initiative, Last Modified 10/8/2019. https://www.epa.gov/superfund-redevelopment-initiative/epa-region-7-leading-environmentalism-and-forwarding.

USEPA. 2019. “Superfund Technical Assistance Needs Assessments (TANAs).” United States Environmental Protection Agency, Last Modified 4/9/2019. accessed 2020. https://www.epa.gov/superfund/technical-assistance-needs-assessments-tanas.

USEPA. 2019. “Drinking Water Treatability Database Introduction.” Last Modified 9-3-2019. accessed 2020. https://www.epa.gov/water-research/drinking-water-treatability-database-tdb.

USEPA. 2019. Technical Brief: Per and Polyfluoroalkyl Substances (PFAS) Incineration to Manage PFAS Waste Streams.

Washington D.C.: U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2019-09/documents/technical_brief_pfas_incineration_ioaa_approved_final_july_2019.pdf.

USEPA. 2019. “Vocabulary Catalog. Terms & Acronyms.” Last Modified December 12, 2019. https://iaspub.epa.gov/sor_internet/registry/termreg/searchandretrieve/termsandacronyms/search.do.

USEPA. 2019. “USEPA Web page for Cyanobacteria.” accessed 2020. https://www.epa.gov/cyanohabs/learn-about-cyanobacteria-and-cyanotoxins.

USEPA. 2019. Systematic Review Protocol for the PFBA, PFHxA, PFHxS, PFNA, and PFDA IRIS Assessments. Washington, DC: U.S. Environmental Protection Agency.

USEPA. 2019. “EPA New Approach Methods: Efforts to Reduce Use of Animals in Chemical Testing.” Last Modified August 31, 2020. https://www.epa.gov/research/epa-new-approach-methods-efforts-reduce-use-animals-chemical-testing.

USEPA. 2019. System toxicological approaches to define and predict the toxicity of Per and Polyfluoroalkyl Substances. USEPA Grant R839481.

USEPA. 2019. “EPA and Partners Describe a Chemical Category Prioritization Approach to Select 75 PFAS for Testing using New Approach Methods.” Last Modified February 26, 2019. https://www.epa.gov/sciencematters/epa-and-partners-describe-chemical-category-prioritization-approach-select-75-pfas.

USEPA. 2019. “PFAS Chemical Lists and Tiered Testing Methods Descriptions.” Last Modified September 4, 2019. https://www.epa.gov/chemical-research/pfas-chemical-lists-and-tiered-testing-methods-descriptions.

USEPA. 2019. Leaching Environmental Framework (LEAF) How-To Guide. OLEM and ORD USEPA. https://www.epa.gov/hw-sw846/leaching-environmental-assessment-framework-leaf-methods-and-guidance.

USEPA. 2019. Memorandum: Interim Recommendations to Address Groundwater Contaminated with Perfluorooctanoic Acid and Perfluorooctansulfonate. OLEM Directive No. 9283.1-47. Washington D.C.: Office of Land and Emergency Management US Environmental Protection Agency. https://www.epa.gov/pfas/interim-recommendations-addressing-groundwater-contaminated-pfoa-and-pfos.

USEPA. 2019. Technical Brief: Per- and Polyfluoroalkyl Substances (PFAS): Reviewing Analytical Methods Data for Environmental Samples. EPA-600-F-19-056. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/water-research/reviewing-pfas-analytical-methods-data-environmental-samples-technical-brief.

USEPA. 2019. Preliminary Effluent Guidelines Program Plan 14. EPA-821-R-19-005: Office of Water U.S. Environmental Protection Agency.

USEPA. 2019. The EPA’s Review of Per- and Polyfluoroalkyl Substances (PFAS) in Industrial Wastewater Discharge. EPA-821-R-19-006: Office of Water U.S. Environmental Protection Agency.

USEPA. 2019. Exposure Factors Handbook Chapter 3 (Update): Ingestion of Water and Other Select Liquids. EPA/600/R-18/259F. Washington, DC: USEPA Office of Research and Development.

USEPA. 2020. “CompTox Chemicals Dashboard.” U. S. Environmental Protection Agency, Last Modified October 26, 2021. https://comptox.epa.gov/dashboard/.

USEPA. 2020. “Drinking Water Treatability Database.” accessed 2020. https://oaspub.epa.gov/tdb/pages/general/home.do.

USEPA. 2020. “Expobox Web Page.” accessed 2020. https://www.epa.gov/expobox.

USEPA. 2020. Method 537.1 Determination of Selected Per- and Polyfluorinated Alkyl Substances in Drinking Water by Solid Phase Extraction and Liquid Chromatography/Tandem Mass Spectrometry (LC/MS/MS). Revision 2.0. Washington D.C.: U.S. Environmental Protection Agency. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=348508&Lab=CESER&simpleSearch=0&showCriteria=2&searchAll=537.1&TIMSType=&dateBeginPublishedPresented=03%2F24%2F2018.

USEPA. 2020. Technical Brief: Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) Methods and guidance for sampling and analyzing water and other environmental media. EPA/600/F-17/022h. Washington, DC.

USEPA. 2020. PFAS Action Plan: Program Update February 2020. 100K20002. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2020-01/documents/pfas_action_plan_feb2020.pdf.

USEPA. 2020. New Approach Methods Work Plan: Reducing use of animals in chemical testing. EPA 615B2001. Washington, DC: U.S. Environmental Protection Agency.

USEPA. 2020. "PFAS/EPA: ToxCast Chemical Inventory." accessed 2020. https://comptox.epa.gov/dashboard/chemical_lists/epapfasinv.

USEPA. 2020. "About the Chemical Safety for Sustainability Research Program." Last Modified March 11, 2020. https://www.epa.gov/aboutepa/about-chemical-safety-sustainability-research-program.

USEPA. 2020. "PFAS/EPA: List of 75 Test Samples (Set 1)." accessed 2020. https://comptox.epa.gov/dashboard/chemical_lists/epapfas75s1.

USEPA. 2020. "PFAS/EPA: List of 75 Test Samples (Set 2)." Accessed 2020. https://comptox.epa.gov/dashboard/chemical_lists/EPAPFAS75S2.

USEPA. 2020. "PFAS Master List of PFAS Substances (Version 2)." Last Modified August 10, 2021. accessed 2021. https://comptox.epa.gov/dashboard/chemical-lists/PFASMASTER.

USEPA. 2020. "PFAS|EPA: PFAS structures in DSSTox." Last Modified August, 2020. accessed 2021. https://comptox.epa.gov/dashboard/chemical_lists/PFASSTRUCTV3.

USEPA. 2020. "EPA PFAS Drinking Water Laboratory Methods." Last Modified April 27, 2020. accessed 2021. https://www.epa.gov/pfas/epa-pfas-drinking-water-laboratory-methods.

USEPA. 2020. "Water Quality Standards Handbook." Last Modified August 31, 2020. accessed 2021. https://www.epa.gov/wqs-tech/water-quality-standards-handbook.

USEPA. 2020. "Toxics Release Inventory (TRI) Program. What is the Toxics Release Inventory?", Last Modified January 14, 2021. accessed 2020. https://www.epa.gov/toxics-release-inventory-tri-program/what-toxics-release-inventory.

USEPA. 2020. Technical Brief: Per- and Polyfluoroalkyl Substances (PFAS): Incineration to Manage PFAS Waste Streams. USEPA. https://www.epa.gov/sites/production/files/2019-09/documents/technical_brief_pfas_incineration_ioaa_approved_final_july_2019.pdf.

USEPA. 2020. "Water Quality Criteria." Last Modified October 7, 2020. accessed 2021. https://www.epa.gov/wqc.

USEPA. 2020. Interim Guidance on Destroying and Disposing of Certain PFAS and PFAS-Containing Materials that are not Consumer Products. EPA-HQ-OLEM-2020-0527-0003. Washington, DC. https://www.epa.gov/pfas/interim-guidance-destroying-and-disposing-certain-pfas-and-pfas-containing-materials-are-not.

USEPA. 2020. Letter from Earl Ingram, Office of Chemical Safety and Pollution Prevention, to Ryan Felton. November 24, 2020.

USEPA. 2020. "Fact Sheets about the Fourth Unregulated Contaminant Monitoring Rule (UCMR4)." accessed 2021. https://www.epa.gov/dwucmr/fact-sheets-about-fourth-unregulated-contaminant-monitoring-rule-ucmr-4.

USEPA. 2020. "Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air." USEPA Ambient Monitoring Technology Information Center. accessed 2021. https://www.epa.gov/amtic/compendium-methods-determination-toxic-organic-compounds-ambient-air.

USEPA. 2020. National Functional Guidelines for Organic Superfund Methods Data Review. EPA 540-R-20-005. Washington, DC: U.S Environmental Protection Agency. https://www.epa.gov/sites/default/files/2021-03/documents/nfg_for_organic_superfund_methods_data_review_novem ber_2020.pdf.

USEPA. 2020. National Functional Guidelines for High Resolution Superfund Methods Data Review. EPA 542-R-20-007. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2021-03/documents/nfg_for_hrsm_superfund_methods_data_review_november_2020.pdf.

USEPA. 2020. Soil Sampling Procedure. LSASDPROC-300-R4. Athens, GA. https://www.epa.gov/sites/default/files/2015-06/documents/Soil-Sampling.pdf.

USEPA. 2021. Human Health Toxicity Values for Perfluorobutane Sulfonic Acid and Related Compound Potassium Perfluorobutane Sulfonate. EPA/600/R-20/345F. Washington, DC. https://ofmpub.epa.gov/eims/eimscomm.getfile?p_download_id=542393.

USEPA. 2021. “Test Methods for Evaluating Solid Waste: Physical/Chemical Methods, SW-846.” accessed 2021. https://www.epa.gov/hw-sw846/sw-846-compendium.

USEPA. 2021. “CWA Analytical Methods for Per- and Polyfluorinated Alkyl Substances.” USEPA Last Modified March 2, 2021. accessed 2021. https://www.epa.gov/cwa-methods/cwa-analytical-methods-and-polyfluorinated-alkyl-substances-pfas.

USEPA. 2021. Method 8327 Per- and Polyfluoroalkyl Substances (PFAS) by Liquid Chromatography/Tandem Mass Spectrometry (LC/MS/MS). Washington, D.C.: USEPA. https://www.epa.gov/hw-sw846/sw-846-test-method-8327-and-polyfluoroalkyl-substances-pfas-liquid-chromatographytandem.

USEPA. 2021. Announcement of Final Regulatory Determinations for Contaminants on the Fourth Drinking Water Contaminant Candidate List. 86 Federal Register 12272: USEPA. https://www.govinfo.gov/content/pkg/FR-2021-03-03/pdf/2021-04184.pdf.

USEPA. 2021. Other Test Method 45 (OTM-45) Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources. https://www.epa.gov/sites/default/files/2021-01/documents/otm_45_semivolatile_pfas_1-13-21.pdf.

USEPA. 2021. Research Brief: Potential PFAS Destruction Technology: Supercritical Water Oxidation. USEPA ORD. https://www.epa.gov/sites/default/files/2021-01/documents/pitt_research_brief_scwo_final_jan_25_2021_508.pdf.

USEPA. 2021. “EPA Announces First Validated Laboratory Method to Test for PFAS in Wastewater, Surface Water Groundwater, Soils.” US Environmental Protection Agency, Last Modified September 2, 2021. accessed 2021. https://www.epa.gov/newsreleases/epa-announces-first-validated-laboratory-method-test-pfas-wastewater-surface-water.

USEPA. 2021. “PFAS Analytical Methods Development and Sampling Research.” USEPA, Last Modified September 8, 2021. accessed 2021. https://www.epa.gov/water-research/pfas-analytical-methods-development-and-sampling-research#:~:text=Standard%20Analytical%20Methods%20%20%20%20Media%20,for%20non-drinking%20...%20%209%20more%20rows%20.

USEPA. 2021. Human Health Toxicity Values for Hexafluoropropylene Oxide (HFPO) Dimer Acid and Its Ammonium Salt (CASRN 13252-13-6 and CASRN 62037-80-3). 822R-21-010. Washington, D.C. https://www.epa.gov/system/files/documents/2021-10/genx-chemicals-toxicity-assessment_tech-edited_oct-21-508.pdf.

USEPA. 2021. PFAS Strategic Roadmap. EPA’s Commitment to Action 2021-2024. Washington, D.C. https://www.epa.gov/system/files/documents/2021-10/pfas-roadmap_final-508.pdf.

USEPA. 2021. “Analyses to support EPA’s National Primary Drinking Water Rulemaking for PFAS.” Last Modified November 16, 2021. accessed 2021. https://sab.epa.gov/ords/sab/f?p=100:18:16490947993:::RP,18:P18_ID:2601.

USEPA. 2021. “Previous Actions to Address PFAS.” Last Modified November 23, 2021. accessed 2021. https://www.epa.gov/pfas/previous-actions-address-pfas.

USEPA. 2021. “EPA Actions to Address PFAS.” Last Modified November 16, 2021. accessed 2021. https://www.epa.gov/pfas/epa-actions-address-pfas.

USEPA. 2021. National PFAS Testing Strategy: Identification of Candidate Per- and Poly-fluoroalkyl Substances (PFAS) for Testing. Washington, DC. https://www.epa.gov/system/files/documents/2021-10/pfas-natl-test-strategy.pdf.

USEPA. 2021. “Regional Screening Levels (RSLs) – Generic Tables. Tables as of November 2021.” Last Modified November 17, 2021. accessed 2021. https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables.

USEPA. 2021. “Draft CCL 5 Chemicals.” Last Modified July 19, 2021. accessed 2021. https://www.epa.gov/ccl/draft-ccl-5-chemicals.

USEPA. 2021. “EPA Responds to New Mexico Governor and Acts to Address PFAS Under Hazardous Waste Law.” Last Modified November 4, 2021. accessed 2021. https://www.epa.gov/newsreleases/epa-responds-new-mexico-governor-and-acts-address-pfas-under-hazardous-waste-law.

USEPA. 2021. Multi-Industry Per- and Polyfluoroalkyl Substances (PFAS) Study – 2021 Preliminary Report. EPA-821-R-21-004. Washington, DC: Office of Water U.S Environmental Protection Agency. https://www.epa.gov/system/files/documents/2021-09/multi-industry-pfas-study_preliminary-2021-report_508_2021.09.08.pdf.

USEPA. 2021. “PFAS Explained.” Last Modified OCtober 18, 2021. accessed 2021. https://www.epa.gov/pfas/pfas-explained.

USEPA. 2021. “Human Health Toxicity Assessments for GenX Chemicals.” Last Modified November 9, 2021. accessed 2021. https://www.epa.gov/chemical-research/human-health-toxicity-assessments-genx-chemicals.

USEPA. 2021. Proposed Approaches to the Derivation of a Draft Maximum Contaminant Level Goal for Perfluorooctanoic Acid (PFOA) (CASRN 335-67-1) in Drinking Water. External Peer Review Draft. EPA 822-D-21-001. Washington, D.C.: U.S. Environmental Protection Agency Office of Water (4304T).

USEPA. 2021. Proposed Approaches to the Derivation of a Draft Maximum Contaminant Level Goal for Perfluorooctane Sulfonic Acid (PFOS) (CASRN 1763-23-1) in Drinking Water. External Peer Review Draft. EPA 822-D-21-002. Washington, D.C.: U.S. Environmental Protection Agency Office of Water (4304T).

USEPA. 2021. Preliminary Effluent Guidelines Program Plan 15. EPA-821-R-21-003: Office of Water U.S. Environmental Protection Agency.

USEPA. 2021. Advanced Notice of Proposed Rulemaking: Clean Water Act Effluent Limitations Guidelines and Standards for the Organic Chemicals, Plastics and Synthetic Fibers Point Source Category. 86 FR 14560. https://www.federalregister.gov/documents/2021/03/17/2021-05402/clean-water-act-effluent-limitations-guidelines-and-standards-for-the-organic-chemicals-plastics-and.

USEPA. 2021. Multi-Industry Per- and Polyfluoroalkyl Substances (PFAS) Study – 2021 Preliminary Report. EPA-821-R-21-004: Office of Water U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2021-09/multi-industry-pfas-study_preliminary-2021-report_508_2021.09.08.pdf.

USEPA. 2021. Provisional Peer-Reviewed Toxicity Values (PPRTVs) Perfluorobutane sulfonic acid (PFBS) CASRN 375-73-5. EPA/690/R-21/001F. https://cfpub.epa.gov/ncea/pprtv/recordisplay.cfm?deid=350061.

USEPA. 2021. Memorandum: EPA’s Analytical Chemistry Branch PFAS Testing Rinses from Selected Fluorinated and Non-Fluorinated HDPE Containers. Washington, D.C.: USEPA – Office of Chemical Safety and Pollution Prevention. https://www.epa.gov/sites/default/files/2021-03/documents/results-of-rinsates-samples_03042021.pdf.

USEPA. 2021. Effluent Guidelines Program Plan 14. EPA-821-R-21-001: U.S. Environmental Protection Agency Office of Water.

USEPA. 2021. The Fifth Unregulated Contaminant Monitoring Rule (UCMR 5) Program Overview Fact Sheet. EPA-815-

F-21-009: U.S. Environmental Protection Agency Office of Water. https://www.epa.gov/system/files/documents/2022-02/ucmr5-factsheet.pdf.

USEPA. 2021. Toxic substances control act reporting and recordkeeping requirements for perfluoroalkyl and polyfluoroalkyl substances. https://www.regulations.gov/document/EPAHQ-OPPT-2020-0549-0001.

USEPA. 2022. “Regional Screening Levels User’s Guide, Introduction.” Last Modified November 29, 2022. accessed 2023. https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide#intro.

USEPA. 2022. “Drinking Water Contaminant Human Health Effects Information.” Last Modified September 16, 2022. accessed 2023. https://www.epa.gov/dwstandardsregulations/drinking-water-contaminant-human-health-effects-information#content.

USEPA. 2022. IRIS Toxicological Review of Perfluorobutanoic Acid (PFBA, CASRN 375-22-4) and Related Salts (Final Report, 2022). EPA/635/R-22/277F. Washington, D.C.: U.S. Environmental Protection Agency. www.epa.gov/iris.

USEPA. 2022. Draft Method 1621. Screening Method for the Determination of Adsorbable Organic Fluorine (AOF) in Aqueous Matrices by Combustion Ion Chromatography (CIC). EPA 821-D-22-002. Washington, D.C.: U.S. Environmental Protection Agency Office of Water (4303T). https://www.epa.gov/cwa-methods/cwa-analytical-methods-and-polyfluorinated-alkyl-substances-pfas.

USEPA. 2022. Draft Aquatic Life Ambient Water Quality Criteria for Perfluorooctanoic Acid (PFOA). EPA-842-D-22-001. Washington, D.C.: U.S. Environmental Protection Agency Office of Water (4303T). https://www.epa.gov/system/files/documents/2022-04/pfoa-report-2022.pdf.

USEPA. 2022. Fact Sheet: Draft 2022 Aquatic Life Ambient Water Quality Criteria for Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonic Acid (PFOS). EPA-842-D-22-005. Washington, D.C.: U.S. Environmental Protection Agency Office of Water (4303T). https://www.epa.gov/system/files/documents/2022-04/pfoa-pfos-draft-factsheet-2022.pdf.

USEPA. 2022. Draft Aquatic Life Ambient Water Quality Criteria for Perfluorooctane Sulfonate (PFOS). EPA-842-D-22-002. Washington, D.C.: U.S. Environmental Protection Agency Office of Water (4303T). https://www.epa.gov/system/files/documents/2022-04/pfos-report-2022.pdf.

USEPA. 2022. Memorandum. Addressing PFAS Discharges in EPA-Issued NPDES Permits and Expectations Where EPA is the Pretreatment Control Authority. Washington, D.C.: U.S. Environmental Protection Agency Office of Water (4303T). https://www.epa.gov/system/files/documents/2022-04/npdes_pfas-memo.pdf.

USEPA. 2022. EPA Response to the External Peer Review of U.S. EPA’s “Draft Aquatic Life Ambient Water Quality Criteria for Perfluorooctanoic Acid (PFOA)”. EPA-842-D-22-004. Washington, DC: U.S. Environmental Protection Agency Office of Water Office of Science and Technology. https://www.epa.gov/wqc/aquatic-life-criteria-perfluorooctanoic-acid-pfoa.

USEPA. 2022. EPA Response to the External Peer Review of U.S. EPA’s “Draft Aquatic Life Ambient Water Quality Criteria for Perfluorooctane Sulfonate (PFOS)”. EPA-842-D-22-003. Washington, DC: U.S. Environmental Protection Agency Office of Water Office of Science and Technology. https://www.epa.gov/wqc/aquatic-life-criteria-perfluorooctane-sulfonate-pfos.

USEPA. 2022. “CMAQ: The Community Multiscale Air Quality Modeling System.” Last Modified March 7, 2022. accessed 2022. https://www.epa.gov/cmaq.

USEPA. 2022. Lifetime Drinking Water Health Advisories for Four Perfluoroalkyl Substances. Washington, DC: U.S. Environmental Protection Agency Office of Water. https://www.govinfo.gov/content/pkg/FR-2022-06-21/pdf/2022-13158.pdf.

USEPA. 2022. “PFAS|EPA: PFAS Structures in DSSTox (update August 2022).” U.S. EPA. accessed 2022. https://comptox.epa.gov/dashboard/chemical-lists/PFASSTRUCTV5.

USEPA. 2022. “PFAS Thermal Treatment Database.” https://www.epa.gov/chemical-research/pfas-thermal-treatment-database-pfastt.

USEPA. 2022. Interim Drinking Water Health Advisory: Perfluorooctanoic Acid (PFOA). CASRN 335-67-1. EPA/822/R-22/003: U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2022-06/interim-pfoa-2022.pdf.

USEPA. 2022. Interim Drinking Water Health Advisory: Perfluorooctane Sulfonic Acid (PFOS). CASRN 1763-23-1. EPA/822/R-22/004: U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2022-06/interim-pfos-2022.pdf.

USEPA. 2022. “Research on Per- and Polyfluoroalkyl Substances (PFAS).” Last Modified November 18, 2022. accessed 2022. https://www.epa.gov/chemical-research/research-and-polyfluoroalkyl-substances-pfas.

USEPA. 2022. EPA’s PFAS Strategic Roadmap: A Year of Progress. EPA-800-K-22-001. Washington, D.C. https://www.epa.gov/pfas.

USEPA. 2022. Memorandum Results of EPA’s Analytical Chemistry Branch Laboratory Study of PFAS Leaching from Fluorinated HDPE Containers. Washington, D.C.: USEPA – Office of Chemical Safety and Pollution Prevention. https://www.epa.gov/system/files/documents/2022-09/EPA%20PFAS%20Container%20Leaching%20Study%2008122022_0.pdf.

USEPA. 2022. “3M Agrees to EPA Order to Sample and Provide Treatment for PFAS Contamination in Drinking Water near Cordova, IL Facility.” Last Modified November 3, 2022. accessed 2023. https://www.epa.gov/newsreleases/3m-agrees-epa-order-sample-and-provide-treatment-pfas-contamination-drinking-water.

USEPA. 2022. “Learn about Risk Communication.” Last Modified July 14, 2022. accessed 2023. https://www.epa.gov/risk-communication/learn-about-risk-communication.

USEPA. 2022. Memorandum. Addressing PFAS Discharges in NPDES Permits and Through the Pretreatment Program and Monitoring Programs. Washington, D.C. https://www.epa.gov/system/files/documents/2022-12/NPDES_PFAS_State%20Memo_December_2022.pdf.

USEPA. 2022. Drinking Water Health Advisory: Hexafluoropropylene Oxide (HFPO) Dimer Acid (CASRN 13252-13-6) and HFPO Dimer Acid Ammonium Salt (CASRN 62037-80-3), Also Known as “GenX Chemicals”. EPA/822/R-22/005. Washington, DC: USEPA Office of Water. https://www.epa.gov/sdwa/drinking-water-health-advisories-has.

USEPA. 2022. Drinking Water Health Advisory: Perfluorobutane Sulfonic Acid (CASRN 375-73-5) and Related Compound Potassium Perfluorobutane Sulfonate (CASRN 29420-49-3). EPA/822/R-22/006. Washington, DC: USEPA Office of Water. https://www.epa.gov/sdwa/drinking-water-health-advisories-has.

USEPA. 2022. Drinking Water Contaminant Candidate List 5-Final. Federal Register 87(218): 68060-68085. Washington, DC.

USEPA. 2022. “EPA Announces New Drinking Water Health Advisories for PFAS Chemicals, $1 Billion in Bipartisan Infrastructure Law Funding to Strengthen Health Protections.” Last Modified June 15, 2022. accessed 2023. https://www.epa.gov/newsreleases/epa-announces-new-drinking-water-health-advisories-pfas-chemicals-1-billion-bipartisan.

USEPA. 2022. “TSCA Section 8(a)(7) Reporting and Recordkeeping Requirements for Perfluoroalkyl and Polyfluoroalkyl Substances.” accessed 2023. https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/tsca-section-8a7-reporting-and-recordkeeping.

USEPA. 2022. “Emerging Contaminations and Federal Facility Contaminants of Concern.” Last Modified December 15, 2022. accessed 2023. https://www.epa.gov/fedfac/emerging-contaminants-and-federal-facility-contaminants-concern.

USEPA. 2022. “Tribal PFAS Monitoring Results.” accessed 2023. https://sdwis.epa.gov/ords/sfdw_pub/r/sfdw/sdwis_fed_reports_public/tribal_pfas.

USEPA. 2022. “Human Health Toxicity Assessments for GenX Chemicals.” Last Modified December 27, 2022. accessed 2023. https://www.epa.gov/chemical-research/human-health-toxicity-assessments-genx-chemicals.

USEPA. 2022. “Clean Air Technology Center Products.” Last Modified November 21, 2022. accessed 2023. https://www.epa.gov/catc/clean-air-technology-center-products#factsheets.

USEPA. 2022. Proposed Rule: Changes to Reporting Requirements for Per- and Polyfluoroalkyl Substances and to Supplier Notifications for Chemicals of Special Concern; Community Right-to-Know Toxic Chemical Release Reporting. Federal Register, Vol. 87, No. 232. https://www.govinfo.gov/content/pkg/FR-2022-12-05/pdf/2022-26022.pdf.

USEPA. 2022. Proposed Rule: Designation of Perfluorooctanoic Acid (PFOA) and Perfluorooctanesufonic Acid (PFOS) as CERCLA Hazardous Substances. Federal Register, Vol 87, No. 171. https://www.govinfo.gov/content/pkg/FR-2022-09-06/pdf/2022-18657.pdf.

USEPA. 2023. “ECOTOX Knowledgebase.” Last Modified March 15, 2023. accessed 2023. https://cfpub.epa.gov/ecotox/.

USEPA. 2023. “Key EPA Actions to Address PFAS.” Last Modified March 14, 2023. accessed 2023. https://www.epa.gov/pfas/key-epa-actions-address-pfas.

USEPA. 2023. “Addition of Certain PFAS to the TRI by the National Defense Authorization Act.” Last Modified March 3, 2023. accessed 2023. https://www.epa.gov/toxics-release-inventory-tri-program/implementing-statutory-addition-certain-and-polyfluoroalkyl.

USEPA. 2023. “Fifth Unregulated Contaminant Monitoring Rule.” Last Modified February 17, 2023. accessed 2023. https://www.epa.gov/dwucmr/fifth-unregulated-contaminant-monitoring-rule.

USEPA. 2023. Framework for Estimating Noncancer Health Risks Associated with Mixtures of Per- and Polyfluoroalkyl Substances (PFAS). EPA 822-P-23-003. Washington, D.C.: U.S. Environmental Protection Agency. Office of Water and Office of Research and Development.

USEPA. 2023. IRIS Toxicological Review of Perfluorohexanoic Acid (PFHxA) [CASRN 307-24-4] and Related Salts. (Final Report, 2023). EPA/635/R-23/027F. Washington, D.C.: U.S. Environmental Protection Agency. www.epa.gov/iris.

USEPA. 2023. “Basic Information About Biosolids.” Last Modified January 18, 2023. accessed 2023. https://www.epa.gov/biosolids/basic-information-about-biosolids.

USEPA. 2023. “Regional Screening Levels (RSLs) – User’s Guide.” Last Modified May 2023. accessed 2023. https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide.

USEPA. 2023. “PFAS Proposed National Primary Drinking Water Regulation.” Last Modified April 7, 2023. accessed 2023. https://www.epa.gov/sdwa/and-polyfluoroalkyl-substances-pfas.

USEPA. 2023. A Message from the IRIS Program. IRIS Program Outlook. https://www.epa.gov/system/files/documents/2023-02/IRIS%20Program%20Outlook_Feb%202023.pdf.

USEPA. 2023. PUBLIC COMMENT DRAFT. Toxicity Assessment and Proposed Maximum Contaminant Level Goal for Perfluorooctanoic Acid (PFOA) in Drinking Water. EPA-822-P-23-005. Washington, DC: USEPA Office of Water (4304T).

USEPA. 2023. PUBLIC COMMENT DRAFT. Toxicity Assessment and Proposed Maximum Contaminant Level Goal for Perfluorooctane Sulfonic Acid (PFOS) in Drinking Water. EPA-822-P-23-007. Washington, DC: USEPA Office of Water (4304T).

USEPA. 2023. IRIS Toxicological Review of Perfluorodecanoic Acid (PFDA) and Related Salts (Public Comment and External Review Draft). EPA/635/R-23/056a. Washington, DC: U.S. Environmental Protection Agency. www.epa.gov/iris.

USEPA. 2023. Maximum Contaminant Level Goal (MCLG) Summary Document for a Mixture of Four Per- and Polyfluoroalkyl Substances (PFAS): GenX Chemicals, PFBS, PFNA and PFHxS. EPA-822-P-23-004. Washington, DC.

USEPA. 2023. Federal Register: PFAS National Primary Drinking Water Regulation Rulemaking. 40 CFR Parts 141 and 142. Washington, DC. https://www.govinfo.gov/content/pkg/FR-2023-03-29/pdf/2023-05471.pdf.

USEPA. 2023. Per- and Poly-Fluoroalkyl Chemical Substances Designated as Inactive on the TSCA Inventory; Significant New Use Rule. Federal Register 88(17): 4937-4945. Washington, DC.

USEPA. 2023. Effluent Guidelines Program Plan 15. EPA-821-R-22-004. Washington, DC. https://www.epa.gov/eg/current-effluent-guidelines-program-plan.

USEPA. 2023. 4th Draft Method 1633. Analysis of Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous, Solid, Biosolids, and Tissue Samples by LC-MS/MS. EPA 821-D-23-001. Washington, DC: USEPA Office of Water (4303T). https://www.epa.gov/cwa-methods/cwa-analytical-methods-and-polyfluorinated-alkyl-substances-pfas#draft-method-1633.

USEPA. 2023. “PFAS Analytic Tools.” USEPA, Enforcement and Compliance History Online (ECHO), Last Modified May 22, 2023. accessed 2023. https://echo.epa.gov/trends/pfas-tools.

USEPA. 2023. “Per- and Polyfluoroalkyl Substances (PFAS).” Last Modified March 14, 2023. accessed 2023. https://www.epa.gov/pfas.

USEPA. 2023. “Now Available: Latest Update to the TSCA Inventory.” Last Modified May 3, 2023. accessed 2023. https://www.epa.gov/chemicals-under-tsca/now-available-latest-update-tsca-inventory-4.

USEPA. 2023. Per- and Poly-Fluoroalkyl Chemical Substances Designated as Inactive on the TSCA Inventory; Significant New Use Rule. https://www.federalregister.gov/documents/2023/01/26/2023-01156/per–and-poly-fluoroalkyl-chemical-substances-designated-as-inactive-on-the-tsca-inventory.

USEPA. 2023. “How EPA’s Recommended Standards and Ecolabels Address Per- and Polyfluoroalkyl Substances (PFAS).” Last Modified June 7, 2023. accessed 2023. https://www.epa.gov/greenerproducts/how-epas-recommended-standards-and-ecolabels-address-and-polyfluoroalkyl-substances.

USEPA. 2023. Framework for TSCA New Chemicals Review of PFAS Premanufacture Notices (PMNs) and Significant New Use Notices (SNUNs). https://www.epa.gov/system/files/documents/2023-06/PFAS%20Framework_Public%20Release_6-28-23_Final_508c.pdf.

USEPA. 2023. Implementing Statutory Addition of Certain Per- and Polyfluoroalkyl Substances to the Toxics Release Inventory Beginning with Reporting Year 2023. EPA-HQ-OPPT-2023-0223-0001. https://www.regulations.gov/document/EPA-HQ-OPPT-2023-0223-0001.

USEPA. 2023. “Changes to TRI Reporting Requirements for Per- and Poly.” https://www.epa.gov/toxics-release-inventory-tri-program/changes-tri-reporting-requirements-and-polyfluoroalkyl.

USEPA. 2023. Memorandum: Verification Analysis for PFAS in Pesticide Products. Washington, D.C.: USEPA – Office of Chemical Safety and Pollution Prevention. https://www.epa.gov/system/files/documents/2023-05/BEAD%20PFAS%20Study%20Results%202023.pdf.

USEPA. 2023. IRIS Toxicological Review of Perfluorohexanesulfonic Acid (PFHxS) and Related Salts (Public Comment and External Review Draft). EPA-635-R-23-056. Wasington, DC. www.epa.gov/iris.

USEPA. 2023. ORD Human Health Toxicity Value for Perfluoropropanoic Acid (CASRN 422-64-0 | DTXSID8059970). EPA/600/R-22-04 2F. Washington, D.C.: USEPA. https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=358291&Lab=CPHEA.

USEPA Science Advisory Board. 2022. Review of EPA’s Analyses to Support EPA’s National Primary Drinking Water Rulemaking for PFAS. Draft. Washington, D.C.: U.S. Environmental Protection Agency.

USFDA. 2016. “Inventory of Effective Food Contact Substance (FCS) Notifications.” U.S. Food and Drug Administration, Last Modified 10/31/2021. accessed 2021. https://www.accessdata.fda.gov/scripts/fdcc/index.cfm?set=fcn

USFDA. 2020. “FDA Statement: FDA Announces Voluntary Agreement with Manufacturers to Phase Out Certain Short-

Chain PFAS Used in Food Packaging." Last Modified 07/31/2020. accessed 2020. https://www.fda.gov/news-events/press-announcements/fda-announces-voluntary-agreement-manufacturers-phase-out-certain-short-chain-pfas-used-food.

USFDA. 2022. "Per and Polyfluoroalkyl Substances (PFAS)." U.S. Food & Drug Administration, Last Modified July 6, 2022. accessed 2023. https://www.fda.gov/food/chemicals/and-polyfluoroalkyl-substances-pfas.

USGS. 2017. "Contaminants of Emerging Concern in the Environment." Last Modified 6-16-17. accessed 2020. https://toxics.usgs.gov/investigations/cec/index.php.

Valsecchi, Sara, Daniela Conti, Riccardo Crebelli, Stefano Polesello, Marianna Rusconi, Michela Mazzoni, Elisabetta Preziosi, Mario Carere, Luca Lucentini, Emanuele Ferretti, Stefania Balzamo, Maria Gabriella Simeone, and Fiorella Aste. 2017. "Deriving environmental quality standards for perfluorooctanoic acid (PFOA) and related short chain perfluorinated alkyl acids." Journal of Hazardous Materials 323:84-98. https://doi.org/10.1016/j.jhazmat.2016.04.055.

van der Veen, Ike, Anne-Charlotte Hanning, Ann Stare, Pim E. G. Leonards, Jacob de Boer, and Jana M. Weiss. 2020. "The effect of weathering on per- and polyfluoroalkyl substances (PFASs) from durable water repellent (DWR) clothing." Chemosphere 249:126100. https://doi.org/10.1016/j.chemosphere.2020.126100.

van Esterik, J. C., L. Bastos Sales, M. E. Dolle, H. Hakansson, M. Herlin, J. Legler, and L. T. van der Ven. 2016. "Programming of metabolic effects in C57BL/6JxFVB mice by in utero and lactational exposure to perfluorooctanoic acid." Arch Toxicol 90 (3):701-15. 10.1007/s00204-015-1488-7.

Van Gossum, Hans, Jessica Bots, Tom Snijkers, Johan Meyer, Sam Van Wassenbergh, Wim De Coen, and Luc De Bruyn. 2009. "Behaviour of damselfly larvae (Enallagma cyathigerum) (Insecta, Odonata) after long-term exposure to PFOS." Environmental Pollution 157 (4):1332-1336. https://doi.org/10.1016/j.envpol.2008.11.031.

Van Rafelghem, Marc J., David R. Mattie, Richard H. Bruner, and Melvin E. Andersen. 1987. "Pathological and Hepatic Ultrastructural Effects of a Single Dose of Perfluoro-n-decanoic Acid in the Rat, Hamster, Mouse, and Guinea Pig." Toxicological Sciences 9 (3):522-540. 10.1093/toxsci/9.3.522.

Vandermoere, Frédéric. 2008. "Hazard Perception, Risk Perception, and the Need for Decontamination by Residents Exposed to Soil Pollution: The Role of Sustainability and the Limits of Expert Knowledge." Risk Analysis 28 (2):387-398. 10.1111/j.1539-6924.2008.01025.x.

Varhol, B.P., and A.R. Varhol. 2022. A Dual Membrane Passive Diffusion Bage Sampler for PFAS in Groundwater. Snellville, GA: Inc. EON Products. https://www.eonpro.com/wp-content/uploads/2022/08/A-DMPDB-for-Sampling-PFAS-in-Groundwater-White-Paper-72022.pdf.

Vecitis, Chad D., Hyunwoong Park, Jie Cheng, Brian T. Mader, and Michael R. Hoffmann. 2008. "Kinetics and Mechanism of the Sonolytic Conversion of the Aqueous Perfluorinated Surfactants, Perfluorooctanoate (PFOA), and Perfluorooctane Sulfonate (PFOS) into Inorganic Products." The Journal of Physical Chemistry A 112 (18):4261-4270. 10.1021/jp801081y.

Vecitis, Chad D., Hyunwoong Park, Jie Cheng, Brian T. Mader, and Michael R. Hoffmann. 2009. "Treatment technologies for aqueous perfluorooctanesulfonate (PFOS) and perfluorooctanoate (PFOA)." Frontiers of Environmental Science & Engineering in China 3 (2):129-151. 10.1007/s11783-009-0022-7.

Vecitis, Chad D., Yajuan Wang, Jie Cheng, Hyunwoong Park, Brian T. Mader, and Michael R. Hoffmann. 2010. "Sonochemical Degradation of Perfluorooctanesulfonate in Aqueous Film-Forming Foams." Environmental Science & Technology 44 (1):432-438. 10.1021/es902444r.

Vedagiri, Usha K., Richard H. Anderson, Heather M. Loso, and Catherine M. Schwach. 2018. "Ambient levels of PFOS and PFOA in multiple environmental media." Remediation Journal 28 (2):9-51. 10.1002/rem.21548.

Vellanki, Bhanu Prakash, Bill Batchelor, and Ahmed Abdel-Wahab. 2013. "Advanced Reduction Processes: A New Class of Treatment Processes." Environmental Engineering Science 30 (5):264-271. 10.1089/ees.2012.0273.

Venkatesan, A.K., and R.U. Halden. 2013. "National inventory of perfluoroalkyl substances in archived U.S. biosolids from the 2001 EPA National Sewage Sludge Survey.” Journal of Hazardous Materials 252-253:413-418. https://doi.org/10.1016/j.jhazmat.2013.03.016.

Venkatesan, Arjun K., and Rolf U. Halden. 2014. “Loss and in situ production of perfluoroalkyl chemicals in outdoor biosolids–soil mesocosms.” Environmental Research 132:321-327. https://doi.org/10.1016/j.envres.2014.04.024.

Venkatesan, Arjun K., and Rolf U. Halden. 2014. “Loss and in situ production of perfluoroalkyl chemicals in outdoor biosolids–soil mesocosms.” Environmental Research 132:321-327. https://doi.org/10.1016/j.envres.2014.04.024.

Ventia. 2019. Improving Measurement Reliability of the PFAS TOP Assay. https://www.ventia.com/ckeditor_assets/attachments/281/ALGA_R_D_Report_Final.pdf.

Vermeirssen, Etiënne L. M., Marc J. F. Suter, and Patricia Burkhardt-Holm. 2006. “Estrogenicity patterns in the Swiss midland river Lützelmurg in relation to treated domestic sewage effluent discharges and hydrology.” Environmental Toxicology and Chemistry 25 (9):2413-2422. https://doi.org/10.1897/05-515R1.1.

Vermont DEQ. 2020. State of Vermont Plan. Deriving Ambient Water Quality Standards for the Emerging Chemicals of Concern: Per- and Polyfluoroalkyl Substances (PFAS). Department of Environmental Conservation Vermont Agency of Natural Resources. https://dec.vermont.gov/sites/dec/files/wsm/docs/VWQS-PFAS-Plan-Report-Final-20200204.pdf.

Vermont DOH. 2016. Memorandum: Perfluorooctanoic acid (PFOA) and Perfluorooctane sulfonic acid (PFOS) Vermont Drinking Water Health Advisory. Burlington, VT: Vermont Department of Health.

Vermont DOH. 2018. Drinking Water Health Advisory for Five PFAS (per- and polyfluorinated alkyl substances). https://www.healthvermont.gov/sites/default/files/documents/pdf/ENV_DW_PFAS_HealthAdvisory.pdf.

Verner, Marc-André, Gérard Ngueta, Elizabeth T. Jensen, Hermann Fromme, Wolfgang Völkel, Unni Cecilie Nygaard, Berit Granum, and Matthew P. Longnecker. 2016. “A Simple Pharmacokinetic Model of Prenatal and Postnatal Exposure to Perfluoroalkyl Substances (PFASs).” Environmental Science & Technology 50 (2):978-986. 10.1021/acs.est.5b04399.

Verner, Marc-André, Gérard Ngueta, Elizabeth T. Jensen, Hermann Fromme, Wolfgang Völkel, Unni Cecilie Nygaard, Berit Granum, and Matthew P. Longnecker. 2016. “Correction to A Simple Pharmacokinetic Model of Prenatal and Postnatal Exposure to Perfluoroalkyl Substances (PFASs).” Environmental Science & Technology 50 (10):5420-5421. 10.1021/acs.est.6b01755.

Verner, M. A., A. E. Loccisano, N. H. Morken, M. Yoon, H. Wu, R. McDougall, M. Maisonet, M. Marcus, R. Kishi, C. Miyashita, M. H. Chen, W. S. Hsieh, M. E. Andersen, H. J. Clewell, 3rd, and M. P. Longnecker. 2015. “Associations of Perfluoroalkyl Substances (PFAS) with Lower Birth Weight: An Evaluation of Potential Confounding by Glomerular Filtration Rate Using a Physiologically Based Pharmacokinetic Model (PBPK).” Environ Health Perspect 123 (12):1317-24. 10.1289/ehp.1408837.

Vestergren, Robin, Urs Berger, Anders Glynn, and Ian T. Cousins. 2012. “Dietary exposure to perfluoroalkyl acids for the Swedish population in 1999, 2005 and 2010.” Environment International 49:120-127. https://doi.org/10.1016/j.envint.2012.08.016.

Vestergren, Robin, and Ian T. Cousins. 2009. “Tracking the Pathways of Human Exposure to Perfluorocarboxylates.” Environmental Science & Technology 43 (15):5565-5575. 10.1021/es900228k.

Viberg, H., I. Lee, and P. Eriksson. 2013. “Adult dose-dependent behavioral and cognitive disturbances after a single neonatal PFHxS dose.” Toxicology 304:185-91. 10.1016/j.tox.2012.12.013.

Vidonish, Julia E., Kyriacos Zygourakis, Caroline A. Masiello, Gabriel Sabadell, and Pedro J. J. Alvarez. 2016. “Thermal Treatment of Hydrocarbon-Impacted Soils: A Review of Technology Innovation for Sustainable Remediation.” Engineering 2 (4):426-437. https://doi.org/10.1016/J.ENG.2016.04.005.

Vierke, Lena, Urs Berger, and Ian T. Cousins. 2013. “Estimation of the Acid Dissociation Constant of Perfluoroalkyl Carboxylic Acids through an Experimental Investigation of their Water-to-Air Transport.” Environmental Science & Technology 47 (19):11032-11039. 10.1021/es402691z.

Vierke, Lena, Claudia Staude, Annegret Biegel-Engler, Wiebke Drost, and Christoph Schulte. 2012. “Perfluorooctanoic acid (PFOA) — main concerns and regulatory developments in Europe from an environmental point of view." Environmental Sciences Europe 24 (1):16. 10.1186/2190-4715-24-16.

Viswanathan, M., A. Ammerman, E. Eng, G. Gartlehner, K. N. Lohr, D. Griffith, S. Rhodes, C. Samuel-Hodge, S. Maty, L. Lux, L. Webb, S. F. Sutton, T. Swinson, A. Jackman, and L. Whitener. 2004. Community-Based Participatory Research: Assessing the Evidence. Evidence Report/Technology Assessment No. 99. AHRQ Publication 04-E022-2. Rockville, MD: Agency for Healthcare Research and Quality.

Vo, Phong H. N., Thomas Buckley, Xiaoyong Xu, Thi Minh Hong Nguyen, Victor Rudolph, and Pradeep Shukla. 2023. "Foam fractionation of per- and polyfluoroalkyl substances (PFASs) in landfill leachate using different cosurfactants." Chemosphere 310:136869. https://doi.org/10.1016/j.chemosphere.2022.136869.

Vogan, J., I. Ross, J. Burdick, and J. Quinnan. 2015. "Advances in PFC investigation and remediation." 2016 Federal Contaminated Sites National Workshop www.rpic-ibic.ca/documents/2016_FCS_NW/Presentation/32_-_Vogan_EN.pdf

Volkwein, Stephan, Hans-Werner Hurtig, and Walter Klöpffer. 1999. "Life Cycle Assessment of Contaminated Sites Remediation." International Journal of Life Cycle Assessment 4:263-274. https://doi.org/10.1007/BF02979178.

Vollet Martin, Kaitlin, Timothy J. Hilbert, Michael Riley, Jay Christian, Anna Hoover, Kelly Pennell, Qunxing Ding, and Erin Haynes. 2022. "PFAS Incineration and Environmental Justice in East Liverpool, Ohio." SSRN. http://dx.doi.org/10.2139/ssrn.4102823.

von der Trenck, Karl Theo, Rainer Konietzka, Annegret Biegel-Engler, Jan Brodsky, Andrea Hädicke, Arnold Quadflieg, Rudolf Stockerl, and Thorsten Stahl. 2018. "Significance thresholds for the assessment of contaminated groundwater: perfluorinated and polyfluorinated chemicals." Environmental Sciences Europe 30 (19). https://doi.org/10.1186/s12302-018-0142-4.

VT ANR. 2021. Notice of Decision Not To Adopt a Maximum Contaminant Level Regulating PFAS as a Class in Public Drinking Water Systems. Vermont Agency of Natural Resources (ANR). https://dec.vermont.gov/sites/dec/files/PFAS/PFAS-MCL-Final-Decision.pdf

VT ANR. 2021. "State seeks additional science before regulating PFAS as a class in public drinking water." accessed 2021. https://anr.vermont.gov/content/state-seeks-additional-science-regulating-pfas-class-public-drinking-water#:~:text=Regulating%20PFAS%20as%20a%20class%20would%20help%20protect,in%20public%20drinking%20water%20using%20current%20state%20standards.

VT ANR. 2022. "State Partners with Local Fire Departments to Safely Get Rid of Toxic Fire-fighting Foam." accessed 2022. https://anr.vermont.gov/node/1276.

VT DEC. 2016. Vermont Evolving Regulations and Emerging Contaminants Presentation. Vermont Department of Environmental Conservation. http://www.vectogether.org/wp-content/uploads/2013/10/Moran-Matt-VEC.Presentation.pdf

VT DEC. 2016. "Emergency Rule Coversheet: Vermont Hazardous Waste Regulations." Last Modified April 16, 2016. http://dec.vermont.gov/sites/dec/files/documents/2016_04_14%20VHWMR%20Signed%20APA%20forms.pdf

VT DEC. 2018. Perfluoroalkyl Substances (PFAS) Contamination Status Report. Vermont Department of Environmental Conservation. https://dec.vermont.gov/sites/dec/files/documents/PFAS%20Sampling%20Report%207.10.18%20FINAL.pdf.

VT DEC. 2018. "News Release: State Partners with Local Fire Departments to Safely Get Rid of Toxic Fire-Fighting Foam." http://www.vermont.gov/portal/government/article.php?news=6853.

WA DER. 2017. Interim Guideline on the Assessment and Management of Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS). Perth, Western Australia: Government of Western Australia. https://www.der.wa.gov.au/images/documents/your-environment/contaminated-sites/guidelines/Guideline-on-Assessment-and-Management-of-PFAS-.pdf

Wagner, A., B. Raue, H. J. Brauch, E. Worch, and F. T. Lange. 2013. "Determination of adsorbable organic fluorine from aqueous environmental samples by adsorption to polystyrene-divinylbenzene based activated carbon and combustion ion chromatography.” J Chromatogr A 1295:82-9. 10.1016/j.chroma.2013.04.051.

Waite, T.D., C.N. Kurucz, W.J. Cooper, and D. Brown. 1998. Full scale electron beam systems for treatment of water, wastewater and medical waste. No. IAEA-TECDOC-1023.

Wallington, T. J., M. D. Hurley, J. Xia, D. J. Wuebbles, S. Sillman, A. Ito, J. E. Penner, D. A. Ellis, J. Martin, S. A. Mabury, O. J. Nielsen, and M. P. Sulbaek Andersen. 2006. “Formation of C7F15COOH (PFOA) and Other Perfluorocarboxylic Acids during the Atmospheric Oxidation of 8:2 Fluorotelomer Alcohol.” Environmental Science & Technology 40 (3):924-930. 10.1021/es051858x.

Walters, Adam, and David Santillo. 2006. Uses of Perfluorinated Substances. GRL-TN-06-2006. Exeter, UK: Greenpeace Research Laboratories. https://www.greenpeace.to/greenpeace/.

Walton, B. 2018. “Perfluorinated Chemicals Health Study Included in Congress Budget Deal.” Circle of Blue. accessed March 22, 2018. https://www.circleofblue.org/2018/world/perfluorinated-chemicals-health-study-included-in-congress-budget-deal/.

Wang, Bin, Yiming Yao, Hao Chen, Shuai Chang, Ying Tian, and Hongwen Sun. 2020. “Per- and polyfluoroalkyl substances and the contribution of unknown precursors and short-chain (C2–C3) perfluoroalkyl carboxylic acids at solid waste disposal facilities.” Science of The Total Environment 705:135832. https://doi.org/10.1016/j.scitotenv.2019.135832.

Wang, Chenyang, Bei Yan, Gabriel Munoz, Sébastien Sauvé, and Jinxia Liu. 2021. “Modified clays reduce leaching of per- and polyfluoroalkyl substances from AFFF-contaminated soils.” AWWA Water Science 3 (5):e1241. https://doi.org/10.1002/aws2.1241.

Wang, Hexing, Hongyi Du, Jiaqi Yang, Hong Jiang, Karmin O, Linji Xu, Shuping Liu, Jianping Yi, Xu Qian, Yue Chen, Qingwu Jiang, and Gengsheng He. 2019. “PFOS, PFOA, estrogen homeostasis, and birth size in Chinese infants.” Chemosphere 221:349-355. https://doi.org/10.1016/j.chemosphere.2019.01.061.

Wang, Junli, Zunhui Lin, Xuexiang He, Mingrui Song, Paul Westerhoff, Kyle Doudrick, and David Hanigan. 2022. “Critical Review of Thermal Decomposition of Per- and Polyfluoroalkyl Substances: Mechanisms and Implications for Thermal Treatment Processes.” Environmental Science & Technology 56 (9):5355-5370. 10.1021/acs.est.2c02251.

Wang, Jinxing, Guohui Shi, Jingzhi Yao, Nan Sheng, Ruina Cui, Zhaoben Su, Yong Guo, and Jiayin Dai. 2020. “Perfluoropolyether carboxylic acids (novel alternatives to PFOA) impair zebrafish posterior swim bladder development via thyroid hormone disruption.” Environment International 134:105317. https://doi.org/10.1016/j.envint.2019.105317.

Wang, Jiaxuan, Lei Wang, Changqing Xu, Rui Zhi, Rui Miao, Tong Liang, Xianglei Yue, Yongtao Lv, and Tingting Liu. 2018. “Perfluorooctane sulfonate and perfluorobutane sulfonate removal from water by nanofiltration membrane: The roles of solute concentration, ionic strength, and macromolecular organic foulants.” Chemical Engineering Journal 332:787-797. https://doi.org/10.1016/j.cej.2017.09.061.

Wang, Jianshe, Xiaoyang Wang, Nan Sheng, Xiujuan Zhou, Ruina Cui, Hongxia Zhang, and Jiayin Dai. 2017. “RNA-sequencing analysis reveals the hepatotoxic mechanism of perfluoroalkyl alternatives, HFPO2 and HFPO4, following exposure in mice.” Journal of Applied Toxicology 37 (4):436-444. https://doi.org/10.1002/jat.3376.

Wang, J., S. Yan, W. Zhang, H. Zhang, and J. Dai. 2015. “Integrated proteomic and miRNA transcriptional analysis reveals the hepatotoxicity mechanism of PFNA exposure in mice.” J Proteome Res 14 (1):330-41. 10.1021/pr500641b.

Wang, Jianshe, Yating Zhang, Fang Zhang, Leo W. Y. Yeung, Sachi Taniyasu, Eriko Yamazaki, Renping Wang, Paul K. S. Lam, Nobuyoshi Yamashita, and Jiayin Dai. 2013. “Age- and gender-related accumulation of perfluoroalkyl substances in captive Chinese alligators (Alligator sinensis).” Environmental Pollution 179:61-67. https://doi.org/10.1016/j.envpol.2013.04.020.

Wang, Li, Bill Batchelor, Suresh D. Pillai, and Venkata S. V. Botlaguduru. 2016. “Electron beam treatment for potable water reuse: Removal of bromate and perfluorooctanoic acid.” Chemical Engineering Journal 302:58-68. https://doi.org/10.1016/j.cej.2016.05.034.

Wang, L., Y. Wang, Y. Liang, J. Li, Y. Liu, J. Zhang, A. Zhang, J. Fu, and G. Jiang. 2013. “Specific accumulation of lipid droplets in hepatocyte nuclei of PFOA-exposed BALB/c mice.” Sci Rep 3:2174. 10.1038/srep02174.

Wang, Ling, Yu Wang, Yong Liang, Jia Li, Yuchen Liu, Jie Zhang, Aiqian Zhang, Jianjie Fu, and Guibin Jiang. 2014. “PFOS induced lipid metabolism disturbances in BALB/c mice through inhibition of low-density lipoproteins excretion.” Scientific Reports 4:4582. https://doi.org/10.1038/srep04582.

Wang, Ning, Robert C. Buck, Bogdan Szostek, Lisa M. Sulecki, and Barry W. Wolstenholme. 2012. “5:3 Polyfluorinated acid aerobic biotransformation in activated sludge via novel “one-carbon removal pathways”.” Chemosphere 87 (5):527-534. https://doi.org/10.1016/j.chemosphere.2011.12.056.

Wang, Ning, Jinxia Liu, Robert C. Buck, Stephen H. Korzeniowski, Barry W. Wolstenholme, Patrick W. Folsom, and Lisa M. Sulecki. 2011. “6:2 Fluorotelomer sulfonate aerobic biotransformation in activated sludge of wastewater treatment plants.” Chemosphere 82 (6):853-858. https://doi.org/10.1016/j.chemosphere.2010.11.003.

Wang, Ning, Bogdan Szostek, Robert C. Buck, Patrick W. Folsom, Lisa M. Sulecki, Vladimir Capka, William R. Berti, and John T. Gannon. 2005. “Fluorotelomer Alcohol BiodegradationDirect Evidence that Perfluorinated Carbon Chains Breakdown.” Environmental Science & Technology 39 (19):7516-7528. 10.1021/es0506760.

Wang, Ning, Bogdan Szostek, Robert C. Buck, Patrick W. Folsom, Lisa M. Sulecki, and John T. Gannon. 2009. “8-2 Fluorotelomer alcohol aerobic soil biodegradation: Pathways, metabolites, and metabolite yields.” Chemosphere 75 (8):1089-1096. https://doi.org/10.1016/j.chemosphere.2009.01.033.

Wang, Ning, Bogdan Szostek, Patrick W. Folsom, Lisa M. Sulecki, Vladimir Capka, Robert C. Buck, William R. Berti, and John T. Gannon. 2005. “Aerobic Biotransformation of 14C-Labeled 8-2 Telomer B Alcohol by Activated Sludge from a Domestic Sewage Treatment Plant.” Environmental Science & Technology 39 (2):531-538. 10.1021/es049466y.

Wang, Po, Jonathan K. Challis, Kim H. Luong, Trisha C. Vera, and Charles S. Wong. 2021. “Calibration of organic-diffusive gradients in thin films (o-DGT) passive samplers for perfluorinated alkyl acids in water.” Chemosphere 263:128325. https://doi.org/10.1016/j.chemosphere.2020.128325.

Wang, Qingning, Mingyue Liu, Hongying Zhao, Ying Chen, Fan Xiao, Wenhai Chu, and Guohua Zhao. 2019. “Efficiently degradation of perfluorooctanoic acid in synergic electrochemical process combining cathodic electro-Fenton and anodic oxidation.” Chemical Engineering Journal 378:122071. https://doi.org/10.1016/j.cej.2019.122071.

Wang, Qi, Yuefei Ruan, Zhen Zhao, Lu Zhang, Xia Hua, Litao Jin, Hao Chen, Yu Wang, Yiming Yao, Paul K. S. Lam, Lingyan Zhu, and Hongwen Sun. 2022. “Per- and polyfluoroalkyl substances (PFAS) in the Three-North Shelter Forest in northern China: First survey on the effects of forests on the behavior of PFAS.” Journal of Hazardous Materials 427:128157. https://doi.org/10.1016/j.jhazmat.2021.128157.

Wang, Siquan, Xiaoping Lin, Qin Li, Chang Liu, Yongyu Li, and Xinhong Wang. 2022. “Neutral and ionizable per-and polyfluoroalkyl substances in the urban atmosphere: Occurrence, sources and transport.” Science of The Total Environment 823:153794. https://doi.org/10.1016/j.scitotenv.2022.153794.

Wang, Shana, Qi Yang, Fei Chen, Jian Sun, Kun Luo, Fubing Yao, Xiaolin Wang, Dongbo Wang, Xiaoming Li, and Guangming Zeng. 2017. “Photocatalytic degradation of perfluorooctanoic acid and perfluorooctane sulfonate in water: A critical review.” Chemical Engineering Journal 328:927-942. https://doi.org/10.1016/j.cej.2017.07.076.

Wang, Wenfeng, Geoff Rhodes, Jing Ge, Xiangyang Yu, and Hui Li. 2020. “Uptake and accumulation of per- and polyfluoroalkyl substances in plants.” Chemosphere 261:127584. https://doi.org/10.1016/j.chemosphere.2020.127584.

Wang, Xiaoping, Mengke Chen, Ping Gong, and Chuanfei Wang. 2019. “Perfluorinated alkyl substances in snow as an atmospheric tracer for tracking the interactions between westerly winds and the Indian Monsoon over western China.” Environment International 124:294-301. https://doi.org/10.1016/j.envint.2018.12.057.

Wang, Xinting, Geoffrey M. Evans, and Paul Stevenson. 2014. “Flooding in a Vertically Rising Gas–Liquid Foam.” Industrial & Engineering Chemistry Research 53 (14):6150-6156. 10.1021/ie4001844.

Wang, Xiaoping, Crispin Halsall, Garry Codling, Zhiyong Xie, Baiqing Xu, Zhen Zhao, Yonggang Xue, Ralf Ebinghaus, and

Kevin C. Jones. 2014. “Accumulation of Perfluoroalkyl Compounds in Tibetan Mountain Snow: Temporal Patterns from 1980 to 2010.” Environmental Science & Technology 48 (1):173-181. 10.1021/es4044775.

Wang, Xia, Baida Kong, Bingnan He, Lai Wei, Jianbo Zhu, Yuanxiang Jin, Yudong Shan, Weitao Wang, Chunqiang Pan, and Zhengwei Fu. 2019. “8:2 Fluorotelomer alcohol causes immunotoxicity and liver injury in adult male C57BL/6 mice.” Environmental Toxicology 34 (2):141-149. https://doi.org/10.1002/tox.22668.

Wang, Y., W. Chang, L. Wang, Y. Zhang, Y. Zhang, M. Wang, Y. Wang, and P. Li. 2019. “A review of sources, multimedia distribution and health risks of novel fluorinated alternatives.” Ecotoxicology and Environmental Safety 182:109402. https://doi.org/10.1016/j.ecoenv.2019.109402.

Wang, Yujuan, Hui Lin, Fangyuan Jin, Junfeng Niu, Jinbo Zhao, Ying Bi, and Ying Li. 2016. “Electrocoagulation mechanism of perfluorooctanoate (PFOA) on a zinc anode: Influence of cathodes and anions.” Science of The Total Environment 557-558:542-550. https://doi.org/10.1016/j.scitotenv.2016.03.114.

Wang, Yuan, Pengyi Zhang, Gang Pan, and Hao Chen. 2008. “Ferric ion mediated photochemical decomposition of perfluorooctanoic acid (PFOA) by 254nm UV light.” Journal of Hazardous Materials 160 (1):181-186. https://doi.org/10.1016/j.jhazmat.2008.02.105.

Wang, Zhanyun, Ian T. Cousins, Martin Scheringer, Robert C. Buck, and Konrad Hungerbühler. 2014. “Global emission inventories for C4–C14 perfluoroalkyl carboxylic acid (PFCA) homologues from 1951 to 2030, Part I: production and emissions from quantifiable sources.” Environment International 70:62-75. https://doi.org/10.1016/j.envint.2014.04.013.

Wang, Zhanyun, Ian T. Cousins, Martin Scheringer, and Konrad Hungerbuehler. 2015. “Hazard assessment of fluorinated alternatives to long-chain perfluoroalkyl acids (PFAAs) and their precursors: Status quo, ongoing challenges and possible solutions.” Environment International 75:172-179. https://doi.org/10.1016/j.envint.2014.11.013.

Wang, Zhanyun, Ian T. Cousins, Martin Scheringer, and Konrad Hungerbühler. 2013. “Fluorinated alternatives to long-chain perfluoroalkyl carboxylic acids (PFCAs), perfluoroalkane sulfonic acids (PFSAs) and their potential precursors.” Environment International 60:242-248. https://doi.org/10.1016/j.envint.2013.08.021.

Wang, Zhanyun, Jamie C. DeWitt, Christopher P. Higgins, and Ian T. Cousins. 2017. “A Never-Ending Story of Per- and Polyfluoroalkyl Substances (PFASs)?” Environmental Science & Technology 51 (5):2508-2518. https://doi.org/10.1021/acs.est.6b04806.

Wang, Z., and S. Stout. 2006. Oil Spill Environmental Forensics: Fingerprinting and Source Identification: Elsevier Science. ISBN No. 9780123695239.

Wang, Zhen, Zhiyong Xie, Wenying Mi, Axel Möller, Hendrik Wolschke, and Ralf Ebinghaus. 2015. “Neutral Poly/Per-Fluoroalkyl Substances in Air from the Atlantic to the Southern Ocean and in Antarctic Snow.” Environmental Science & Technology 49 (13):7770-7775. 10.1021/acs.est.5b00920.

Wang, Zhen, Zhiyong Xie, Wenying Mi, Axel Möller, Hendrik Wolschke, and Ralf Ebinghaus. 2015. “Neutral Poly/Per-Fluoroalkyl Substances in Air from the Atlantic to the Southern Ocean and in Antarctic Snow.” Environmental Science & Technology 49 (13):7770-7775. 10.1021/acs.est.5b00920.

Wania, Frank. 2007. “A Global Mass Balance Analysis of the Source of Perfluorocarboxylic Acids in the Arctic Ocean.” Environmental Science & Technology 41 (13):4529-4535. 10.1021/es070124c.

Wanninayake, Dushanthi M. 2021. “Comparison of currently available PFAS remediation technologies in water: A review.” Journal of Environmental Management 283:111977. https://doi.org/10.1016/j.jenvman.2021.111977.

Warne, Michael, Graeme Batley, Rick van Dam, John Chapman, David Fox, Christopher Hickey, and Jenny Stauber. 2018. Revised method for deriving Australian and New Zealand water quality guideline values for toxicants. https://doi.org/10.13140/RG.2.2.36577.35686.

Washington Department of Ecology. 2017. Quality Assurance Project Plan; Statewide Survey of Per- and Poly-fluoroalkyl Substances in Washington State Rivers and Lakes.

Washington Department of Ecology. 2019. Interim Chemical Action Plan for Per- and Polyfluoroalkyl Substances. 18-04-005, Revised January 2019. Olympia, WA. https://apps.ecology.wa.gov/publications/documents/1804005.pdf.

Washington, John W., J. Jackson Ellington, Thomas M. Jenkins, John J. Evans, Hoon Yoo, and Sarah C. Hafner. 2009. “Degradability of an Acrylate-Linked, Fluorotelomer Polymer in Soil.” Environmental Science & Technology 43 (17):6617-6623. 10.1021/es9002668.

Washington, John W., and Thomas M. Jenkins. 2015. “Abiotic Hydrolysis of Fluorotelomer-Based Polymers as a Source of Perfluorocarboxylates at the Global Scale.” Environmental Science & Technology 49 (24):14129-14135. 10.1021/acs.est.5b03686.

Washington, John W., Thomas M. Jenkins, Keegan Rankin, and Jonathan E. Naile. 2015. “Decades-Scale Degradation of Commercial, Side-Chain, Fluorotelomer-Based Polymers in Soils and Water.” Environmental Science & Technology 49 (2):915-923. 10.1021/es504347u.

Washington, John W., Jonathan E. Naile, Thomas M. Jenkins, and David G. Lynch. 2014. “Characterizing Fluorotelomer and Polyfluoroalkyl Substances in New and Aged Fluorotelomer-Based Polymers for Degradation Studies with GC/MS and LC/MS/MS.” Environmental Science & Technology 48 (10):5762-5769. 10.1021/es500373b.

Washington, J. W., K. Rankin, E. L. Libelo, D. G. Lynch, and M. Cyterski. 2018. “Determining global background soil PFAS loads and the fluorotelomer-based polymer degradation rates that can account for these loads.” Science of The Total Environment 651:2444-2449.

Washington, John W., Charlita G. Rosal, James P. McCord, Mark J. Strynar, Andrew B. Lindstrom, Erica L. Bergman, Sandra M. Goodrow, Haile K. Tadesse, Andrew N. Pilant, Benjamin J. Washington, Mary J. Davis, Brittany G. Stuart, and Thomas M. Jenkins. 2020. “Nontargeted mass-spectral detection of chloroperfluoropolyether carboxylates in New Jersey soils.” Science 368 (6495):1103. https://doi.org/10.1126/science.aba7127.

Washington, John W., Hoon Yoo, J. Jackson Ellington, Thomas M. Jenkins, and E. Laurence Libelo. 2010. “Concentrations, Distribution, and Persistence of Perfluoroalkylates in Sludge-Applied Soils near Decatur, Alabama, USA.” Environmental Science & Technology 44 (22):8390-8396. https://doi.org/10.1021/es1003846.

Washington Senate. 2018. Washington Senate Bill 6413 (2018). Engrossed Substitute Senate Bill 6413. 65th Legislature 2018 Regular Session. http://lawfilesext.leg.wa.gov/biennium/2017-18/Pdf/Bills/Senate%20Passed%20Legislature/6413-S.PL.pdf.

Washington State Department of Ecology. 2018. PFAS Chemical Action Plan Focus Sheet. https://fortress.wa.gov/ecy/publications/SummaryPages/1804002.

Washington State Department of Ecology. 2020. Per- and Polyfluoroalkyl Substances. Draft Chemical Action Plan. 20-04-035. Olympia, WA. https://fortress.wa.gov/ecy/publications/summarypages/2004035.html.

Washington State Department of Ecology. 2021. Children’s Safe Products Reporting Rule Rationale for Reporting List of Chemicals of High Concern to Children 2011-2017. 18-04-025. Olympia, WA: Hazardous Waste and Toxics Reduction Program. https://apps.ecology.wa.gov/publications/documents/1804025.pdf.

Washington State Department of Ecology and Washington State Department of Health. 2019. Interim Chemical Action Plan for Per- and Polyfluorinated Alkyl Substances. Publication 18-04-005. https://fortress.wa.gov/ecy/publications/documents/1804005.pdf

Washington State Legislature. 2006. Persistent Bioaccumulative Toxins. Washington Administrative Code 173-333. http://apps.leg.wa.gov/wac/default.aspx?cite=173-333

Washington State Legislature. 2008. Identification of high priority chemicals – Report. RCW 70.240.030. http://apps.leg.wa.gov/RCW/default.aspx?cite=70.240.030

Washington State Legislature. 2018. Class B firefighting foams. Senate Bill 6413. http://lawfilesext.leg.wa.gov/biennium/2017-18/Pdf/Bills/Senate%20Bills/6413.pdf.

Washington State Legislature. 2018. Firefighting Agents and Equipment – Toxic Chemical Use. Chapter 70.75A RCW.

http://app.leg.wa.gov/RCW/default.aspx?cite=70.75A.

Washington State Legislature. 2018. Packages containing metals and toxic chemicals. Chapter 70.95G RCW. http://app.leg.wa.gov/RCW/default.aspx?cite=70.95G.

Watanabe, M.X., T. Kunisue, L. Tao, K. Kannan, A. Subramanian, S. Tanabe, and H. Iwata. 2010. “Dioxin-like and perfluorinated compounds in pigs in an Indian open waste dumping site: Toxicokinetics and effects on hepatic cytochrome P450 and blood plasma hormones.” Environmental Toxicology and Chemistry 29 (7):1551-1560. https://doi.org/10.1002/etc.189.

Watanabe, N., M. Takata, S. Takemine, and K. Yamamoto. 2018. “Thermal mineralization behavior of PFOA, PFHxA, and PFOS during reactivation of granular activated carbon (GAC) in nitrogen atmosphere.” Environ Sci Pollut Res Int 25 (8):7200-7205. 10.1007/s11356-015-5353-2.

Watanabe, N., S. Takemine, K. Yamamoto, Y. Haga, and M. Takate. 2016. “Residual Organic Fluorinated Compounds from Thermal Treatment of PFOA, PFHxA, and PFOS Adsorbed onto GAC.” J Material Cycles and Waste Management 18:625-630. DOI 10.1007/s10163-016-0532-x.

Watts, Richard, J., Judith Sarasa, Frank Loge, J., and Amy L. Teel. 2005. “Oxidative and Reductive Pathways in Manganese-Catalyzed Fenton’s Reactions.” Journal of Environmental Engineering 131 (1):158-164. 10.1061/(ASCE)0733-9372(2005)131:1(158).

Weatherly, Lisa M., Hillary L. Shane, Ewa Lukomska, Rachel Baur, and Stacey E. Anderson. 2023. “Systemic toxicity induced by topical application of perfluoroheptanoic acid (PFHpA), perfluorohexanoic acid (PFHxA), and perfluoropentanoic acid (PFPeA) in a murine model.” Food and Chemical Toxicology 171:113515. https://doi.org/10.1016/j.fct.2022.113515.

Weber, Andrea K., Larry B. Barber, Denis R. LeBlanc, Elsie M. Sunderland, and Chad D. Vecitis. 2017. “Geochemical and Hydrologic Factors Controlling Subsurface Transport of Poly- and Perfluoroalkyl Substances, Cape Cod, Massachusetts.” Environmental Science & Technology 51 (8):4269-4279. 10.1021/acs.est.6b05573.

Weber, Olaf, Roland W. Scholz, Renate Bühlmann, and Dirk Grasmück. 2001. “Risk Perception of Heavy Metal Soil Contamination and Attitudes toward Decontamination Strategies.” Risk Analysis 21 (5):967-967. 10.1111/0272-4332.215165.

Weber, Roland, Alan Watson, Martin Forter, and Fardin Oliaei. 2011. “Review Article: Persistent organic pollutants and landfills – a review of past experiences and future challenges.” Waste Management & Research 29 (1):107-121. 10.1177/0734242X10390730.

Wei, Changlong, Xin Song, Qing Wang, and Zhihao Hu. 2017. “Sorption kinetics, isotherms and mechanisms of PFOS on soils with different physicochemical properties.” Ecotoxicology and Environmental Safety 142:40-50. https://doi.org/10.1016/j.ecoenv.2017.03.040.

Wei, Yanhong, Xiongjie Shi, Hongxia Zhang, Jianshe Wang, Bingsheng Zhou, and Jiayin Dai. 2009. “Combined effects of polyfluorinated and perfluorinated compounds on primary cultured hepatocytes from rare minnow (Gobiocypris rarus) using toxicogenomic analysis.” Aquatic Toxicology 95 (1):27-36. https://doi.org/10.1016/j.aquatox.2009.07.020.

Wei, Zongsu, Tianyuan Xu, and Dongye Zhao. 2019. “Treatment of per- and polyfluoroalkyl substances in landfill leachate: status, chemistry and prospects.” Environmental Science: Water Research & Technology 5 (11):1814-1835. 10.1039/C9EW00645A.

Weinberg, Ingo, Annekatrin Dreyer, and Ralf Ebinghaus. 2011. “Landfills as sources of polyfluorinated compounds, polybrominated diphenyl ethers and musk fragrances to ambient air.” Atmospheric Environment 45 (4):935-941. https://doi.org/10.1016/j.atmosenv.2010.11.011.

Weiner, Barbara, Leo Yeung, Erin Marchington, Lisa D’Agostino, and Scott Mabury. 2013. “Organic fluorine content in aqueous film forming foams (AFFFs) and biodegradation of the foam component 6 : 2 fluorotelomermercaptoalkylamido sulfonate (6 : 2 FTSAS).” Environmental Chemistry 10 (6):486-493. https://doi.org/10.1071/EN13128.

Weir, Scott M., Jamie G. Suski, and Christopher J. Salice. 2010. “Ecological risk of anthropogenic pollutants to reptiles: Evaluating assumptions of sensitivity and exposure.” Environmental Pollution 158 (12):3596-3606. https://doi.org/10.1016/j.envpol.2010.08.011.

Weiß, Odulf, Gerhard A. Wiesmüller, Anne Bunte, Thomas Göen, Carsten K. Schmidt, Michael Wilhelm, and Jürgen Hölzer. 2012. “Perfluorinated compounds in the vicinity of a fire training area – Human biomonitoring among 10 persons drinking water from contaminated private wells in Cologne, Germany.” International Journal of Hygiene and Environmental Health 215 (2):212-215. https://doi.org/10.1016/j.ijheh.2011.08.016.

Wen, Bei, Longfei Li, Yu Liu, Hongna Zhang, Xiaoyu Hu, Xiao-quan Shan, and Shuzhen Zhang. 2013. “Mechanistic studies of perfluorooctane sulfonate, perfluorooctanoic acid uptake by maize (Zea mays L. cv. TY2).” Plant and Soil 370 (1):345-354. https://doi.org/10.1007/s11104-013-1637-9.

Wen, B., Y. Wu, H. Zhang, Y. Liu, X. Hu, H. Huang, and S. Zhang. 2016. “The roles of protein and lipid in the accumulation and distribution of perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) in plants grown in biosolids-amended soils.” Environ Pollut 216:682-688. 10.1016/j.envpol.2016.06.032.

Wenning, Richard J., and Gerald A. Erickson. 1994. “Interpretation and analysis of complex environmental data using chemometric methods.” TrAC Trends in Analytical Chemistry 13 (10):446-457. https://doi.org/10.1016/0165-9936(94)85026-7.

Wesley, M.L., P.V. Doskey, and J.D. Shannon. 2002. Deposition Parameterizations for the Industrial Source Complex (ISC3) Model. Draft ANL report ANL/ER/TRB01/003. Argonne, IL: Argonne National Laboratory. https://gaftp.epa.gov/Air/aqmg/SCRAM/models/preferred/aermod/driscpr.zip.

Weston Solutions, Inc. 2020. Thermal Oxidizer Control Efficiency Compliance Test Report. Test Dates: 28-29 February 2020. W.O. No. 15418.002.023. Fayetteville, NC.

Weston-ER Federal Services. 2022. Final Data Gap Investigation Report, Data Gap Investigations and Streamlined EE/CAs to Support Non-Time Critical Removal Actions, Sites AFFF Area 1 and AFFF Area 21, Wright-Patterson Air Force Base, Dayton, Montgomery County, Ohio. https://ar.afcec-cloud.af.mil/621244.pdf?token=PXxWU4PIFJcfnBlCmuuShFGJ9dJUbmjXd7nlGKs8GQE1.

Westreich, Philippe, Richard Mimna, Jenalle Brewer, and Frederic Forrester. 2018. “The removal of short-chain and long-chain perfluoroalkyl acids and sulfonates via granular activated carbons: A comparative column study.” Remediation Journal 29 (1):19-26. 10.1002/rem.21579.

White, Natasha D., Len Balthis, Kurunthachalam Kannan, Amila O. De Silva, Qian Wu, Katherine M. French, James Daugomah, Christine Spencer, and Patricia A. Fair. 2015. “Elevated levels of perfluoroalkyl substances in estuarine sediments of Charleston, SC.” Science of The Total Environment 521-522:79-89. https://doi.org/10.1016/j.scitotenv.2015.03.078.

White, S. S., A. M. Calafat, Z. Kuklenyik, L. Villanueva, R. D. Zehr, L. Helfant, M. J. Strynar, A. B. Lindstrom, J. R. Thibodeaux, C. Wood, and S. E. Fenton. 2007. “Gestational PFOA exposure of mice is associated with altered mammary gland development in dams and female offspring.” Toxicol Sci 96 (1):133-44. 10.1093/toxsci/kfl177.

White, S. S., K. Kato, L. T. Jia, B. J. Basden, A. M. Calafat, E. P. Hines, J. P. Stanko, C. J. Wolf, B. D. Abbott, and S. E. Fenton. 2009. “Effects of perfluorooctanoic acid on mouse mammary gland development and differentiation resulting from cross-foster and restricted gestational exposures.” Reprod Toxicol 27 (3-4):289-298. 10.1016/j.reprotox.2008.11.054.

White, S. S., J. P. Stanko, K. Kato, A. M. Calafat, E. P. Hines, and S. E. Fenton. 2011. “Gestational and chronic low-dose PFOA exposures and mammary gland growth and differentiation in three generations of CD-1 mice.” Environ Health Perspect 119 (8):1070-6. 10.1289/ehp.1002741.

Whitehead, Heather D., Marta Venier, Yan Wu, Emi Eastman, Shannon Urbanik, Miriam L. Diamond, Anna Shalin, Heather Schwartz-Narbonne, Thomas A. Bruton, Arlene Blum, Zhanyun Wang, Megan Green, Meghanne Tighe, John T. Wilkinson, Sean McGuinness, and Graham F. Peaslee. 2021. “Correction to “Fluorinated Compounds in North American Cosmetics”.” Environmental Science & Technology Letters 8 (12):1104-1105. 10.1021/acs.estlett.1c00903.

Whitehead, Heather D., Marta Venier, Yan Wu, Emi Eastman, Shannon Urbanik, Miriam L. Diamond, Anna Shalin, Heather Schwartz-Narbonne, Thomas A. Bruton, Arlene Blum, Zhanyun Wang, Megan Green, Meghanne Tighe, John T. Wilkinson, Sean McGuinness, and Graham F. Peaslee. 2021. “Fluorinated Compounds in North American Cosmetics.” Environmental Science & Technology Letters 8 (7):538-544. 10.1021/acs.estlett.1c00240.

WI DNR. 2022. “PFAS and Foam on Waterways.” accessed 2023. https://dnr.wisconsin.gov/topic/PFAS/Foam.

Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. New York: Springer-Verlag. https://ggplot2.tidyverse.org.

Wilcox, M. 2022. “Pesticides Are Spreading Toxic “Forever Chemicals,” Scientists Warn.” Scientific American, Last Modified June 15, 2022. accessed 2022. https://www.scientificamerican.com/article/pesticides-are-spreading-toxic-lsquo-forever-chemicals-rsquo-scientists-warn/.

Wilkinson, John L., Peter S. Hooda, Julian Swinden, James Barker, and Stephen Barton. 2017. “Spatial distribution of organic contaminants in three rivers of Southern England bound to suspended particulate material and dissolved in water.” Science of The Total Environment 593-594:487-497. https://doi.org/10.1016/j.scitotenv.2017.03.167.

Wilkinson, John L., Julian Swinden, Peter S. Hooda, James Barker, and Stephen Barton. 2016. “Markers of anthropogenic contamination: A validated method for quantification of pharmaceuticals, illicit drug metabolites, perfluorinated compounds, and plasticisers in sewage treatment effluent and rain runoff.” Chemosphere 159:638-646. https://doi.org/10.1016/j.chemosphere.2016.06.039.

Willach, Sarah, Heinz-Jürgen Brauch, and Frank T. Lange. 2016. “Contribution of selected perfluoroalkyl and polyfluoroalkyl substances to the adsorbable organically bound fluorine in German rivers and in a highly contaminated groundwater.” Chemosphere 145:342-350. https://doi.org/10.1016/j.chemosphere.2015.11.113.

Willett, A., and M. Geary. 2021. “The Versatility of Organoclay and Surface-Modified Clay for Remediation.” 37th Annual International Conference on Soils, Sediments, Water, and Energy (Virtual), October 18-21, 2021.

Willey, J.L. 2021. Determination of Perfluorooctanoic acid and Perfluorooctane sulfonic acid in Aqueous File Forming Foam (AFFF) for Demonstration of Compliance to MIL-PRF-24385. DoD AFFF01, Rev. 1.0. https://www.denix.osd.mil/edqw/documents/documents/dod-afff01-rev-1-0-dtd-7-dec-2021/DoD%20AFFF01%20Rev%201.0%20%20dtd%20%207%20Dec%202021-1.pdf.

Williams, A., A. McEachran, M. Strynar, C. Grulke, K. Mansouri, G. Patlewicz, R. Sams, E. Schymanski, and A. Richard. 2018. ” Accessing information for Per- & Polyfluoroalkyl Substances using the US EPA CompTox Chemistry Dashboard.” American Chemical Society Fall Meeting, Boston, MA, August 19 – 23, 2018 https://doi.org/10.23645/epacomptox.7140953.

Williams, Antony J., Linda G. T. Gaines, Christopher M. Grulke, Charles N. Lowe, Gabriel F. B. Sinclair, Vicente Samano, Inthirany Thillainadarajah, Bryan Meyer, Grace Patlewicz, and Ann M. Richard. 2022. “Assembly and Curation of Lists of Per- and Polyfluoroalkyl Substances (PFAS) to Support Environmental Science Research.” Frontiers in Environmental Science 10. 10.3389/fenvs.2022.850019.

Williams, Antony J., Christopher M. Grulke, Jeff Edwards, Andrew D. McEachran, Kamel Mansouri, Nancy C. Baker, Grace Patlewicz, Imran Shah, John F. Wambaugh, Richard S. Judson, and Ann M. Richard. 2017. “The CompTox Chemistry Dashboard: a community data resource for environmental chemistry.” Journal of Cheminformatics 9 (1):61. https://doi.org/10.1186/s13321-017-0247-6.

Winchell, Lloyd J., John J. Ross, Dominic A. Brose, Thaís B. Pluth, Xavier Fonoll, John W. Norton Jr, and Katherine Y. Bell. 2022. “Pyrolysis and gasification at water resource recovery facilities: Status of the industry.” Water Environment Research 94 (3):e10701. https://doi.org/10.1002/wer.10701.

Winchell, Lloyd J., John J. Ross, Martha J. M. Wells, Xavier Fonoll, John W. Norton Jr, and Katherine Y. Bell. 2021. “Per- and polyfluoroalkyl substances thermal destruction at water resource recovery facilities: A state of the science review.” Water Environment Research 93 (6):826-843. https://doi.org/10.1002/wer.1483.

Winkens, Kerstin, Georgios Giovanoulis, Jani Koponen, Robin Vestergren, Urs Berger, Anne M. Karvonen, Juha Pekkanen, Hannu Kiviranta, and Ian T. Cousins. 2018. “Perfluoroalkyl acids and their precursors in floor dust of children’s bedrooms – Implications for indoor exposure.” Environment International 119:493-502. https://doi.org/10.1016/j.envint.2018.06.009.

Winkens, Kerstin, Jani Koponen, Jasmin Schuster, Mahiba Shoeib, Robin Vestergren, Urs Berger, Anne M. Karvonen, Juha Pekkanen, Hannu Kiviranta, and Ian T. Cousins. 2017. “Perfluoroalkyl acids and their precursors in indoor air sampled in children’s bedrooms.” Environmental Pollution 222:423-432. https://doi.org/10.1016/j.envpol.2016.12.010.

Winquist, A., and K. Steenland. 2014. “Perfluorooctanoic acid exposure and thyroid disease in community and worker cohorts.” Epidemiology 25 (2):255-64. 10.1097/ede.0000000000000040.

Winquist, A., and K. Steenland. 2014. “Modeled PFOA exposure and coronary artery disease, hypertension, and high cholesterol in community and worker cohorts.” Environ Health Perspect 122 (12):1299-305. 10.1289/ehp.1307943.

Witteveen+Bos and TTE. 2016. Emerging Contaminants, PFOS and PFOA, Production Use-Sources, Production and Applications. Commissioned by RWS Leefomgeving (the Netherlands) and OVAM (Flanders). https://emergingcontaminants.eu/index.php/background-info/Factsheets-PFOS-intro.

Wolf, C. J., S. E. Fenton, J. E. Schmid, A. M. Calafat, Z. Kuklenyik, X. A. Bryant, J. Thibodeaux, K. P. Das, S. S. White, C. S. Lau, and B. D. Abbott. 2007. “Developmental toxicity of perfluorooctanoic acid in the CD-1 mouse after cross-foster and restricted gestational exposures.” Toxicol Sci 95 (2):462-73. 10.1093/toxsci/kfl159.

Wolf, Cynthia J., Cynthia V. Rider, Christopher Lau, and Barbara D. Abbott. 2014. “Evaluating the additivity of perfluoroalkyl acids in binary combinations on peroxisome proliferator-activated receptor-α activation.” Toxicology 316:43-54. https://doi.org/10.1016/j.tox.2013.12.002.

Wolf, C. J., R. D. Zehr, J. E. Schmid, C. Lau, and B. D. Abbott. 2010. “Developmental effects of perfluorononanoic Acid in the mouse are dependent on peroxisome proliferator-activated receptor-alpha.” PPAR Res 2010. 10.1155/2010/282896.

Wolf, D. C., T. Moore, B. D. Abbott, M. B. Rosen, K. P. Das, R. D. Zehr, A. B. Lindstrom, M. J. Strynar, and C. Lau. 2008. “Comparative hepatic effects of perfluorooctanoic acid and WY 14,643 in PPAR-alpha knockout and wild-type mice.” Toxicol Pathol 36 (4):632-9. 10.1177/0192623308318216.

Wong, Fiona, Mahiba Shoeib, Athanasios Katsoyiannis, Sabine Eckhardt, Andreas Stohl, Pernilla Bohlin-Nizzetto, Henrik Li, Phil Fellin, Yushan Su, and Hayley Hung. 2018. “Assessing temporal trends and source regions of per- and polyfluoroalkyl substances (PFASs) in air under the Arctic Monitoring and Assessment Programme (AMAP).” Atmospheric Environment 172:65-73. https://doi.org/10.1016/j.atmosenv.2017.10.028.

Wood. 2020. Final Expanded Site Inspection Report for Per- and Polyfluoroalkyl Substances, 105th Airlift Wing, New York Air National Guard, Stewart Air National Guard Base, Newburgh, NY. https://ar.afcec-cloud.af.mil/602198.pdf?token=WuUzcA_kyY5mHtja3s2w8IgqY5ppTcDASEj9NoYr3c81.

Wood Environment & Infrastructure. 2020. The use of PFAS and fluorine-free alternatives in fire-fighting foams. Final report. Specific contracts No 07.0203/2018/791749/ENV.B.2 and ECHA/2018/561. https://echa.europa.eu/documents/10162/28801697/pfas_flourine-free_alternatives_fire_fighting_en.pdf/d5b24e2a-d027-0168-cdd8-f723c675fa98.

Woodard, Steve, John Berry, and Brandon Newman. 2017. “Ion exchange resin for PFAS removal and pilot test comparison to GAC.” Remediation Journal 27 (3):19-27. 10.1002/rem.21515.

Woodward, M., J. Becanova, and R. Lohmann. 2022. Michigan PFAS Sampling at Air Monitoring Sites. University of Rhode Island. https://www.michigan.gov/pfasresponse.

World Bank. 2017. “GEF Grant to Assist China’s Efforts to Phase Out POPs.” World Bank Group, Last Modified April 7. http://www.worldbank.org/en/news/press-release/2017/04/07/gef-grant-to-assist-china-efforts-to-phase-out-pops.

World Bank. 2017. “China – Reduction and Phase-Out of PFOS in Priority Sectors Project.” World Bank Group. http://www.worldbank.org/en/news/loans-credits/2017/04/07/china-reduction-and-phase-out-of-pfos-in-priority-sectors-project

Worley, Rachel Rogers, Susan McAfee Moore, Bruce C. Tierney, Xiaoyun Ye, Antonia M. Calafat, Sean Campbell, Million B. Woudneh, and Jeffrey Fisher. 2017. "Per- and polyfluoroalkyl substances in human serum and urine samples from a residentially exposed community." Environment International 106:135-143. https://doi.org/10.1016/j.envint.2017.06.007.

Woudneh, Million B., Bharat Chandramouli, Coreen Hamilton, and Richard Grace. 2019. "Effect of Sample Storage on the Quantitative Determination of 29 PFAS: Observation of Analyte Interconversions during Storage." Environmental Science & Technology 53 (21):12576-12585. https://doi.org/10.1021/acs.est.9b03859.

Wu, Boran, Shilai Hao, Younjeong Choi, Christopher P. Higgins, Rula Deeb, and Timothy J. Strathmann. 2019. "Rapid Destruction and Defluorination of Perfluorooctanesulfonate by Alkaline Hydrothermal Reaction." Environmental Science & Technology Letters 6 (10):630-636. 10.1021/acs.estlett.9b00506.

Wu, Rongben, Huiju Lin, Eriko Yamazaki, Sachi Taniyasu, Mattias Sörengård, Lutz Ahrens, Paul K. S. Lam, Heesoo Eun, and Nobuyoshi Yamashita. 2021. "Simultaneous analysis of neutral and ionizable per- and polyfluoroalkyl substances in air." Chemosphere 280:130607. https://doi.org/10.1016/j.chemosphere.2021.130607.

Wu, Yaoxing, and Victor W. C. Chang. 2011. "The Effect of Surface Adsorption and Molecular Geometry on the Determination of Henry's Law Constants for Fluorotelomer Alcohols." Journal of Chemical & Engineering Data 56 (8):3442-3448. 10.1021/je200466w.

Wu, Yongming, Mi Deng, Yuanxiang Jin, Xin Liu, Zhaohuan Mai, Hailin You, Xiyan Mu, Xiaoli He, Reem Alharthi, Daniel Joseph Kostyniuk, Chunyan Yang, and Wenqing Tu. 2019. "Toxicokinetics and toxic effects of a Chinese PFOS alternative F-53B in adult zebrafish." Ecotoxicology and Environmental Safety 171:460-466. https://doi.org/10.1016/j.ecoenv.2019.01.010.

Wu, Yongming, Mi Deng, Yuanxiang Jin, Xiyan Mu, Xiaoli He, Nha-Thi Luu, Chunyan Yang, and Wenqing Tu. 2019. "Uptake and elimination of emerging polyfluoroalkyl substance F-53B in zebrafish larvae: Response of oxidative stress biomarkers." Chemosphere 215:182-188. https://doi.org/10.1016/j.chemosphere.2018.10.025.

Wurl, Oliver, Werner Ekau, William M. Landing, and Christopher J. Zappa. 2017. "Sea surface microlayer in a changing ocean – A perspective." Elementa: Science of the Anthropocene 5. 10.1525/elementa.228.

WV DEP. 2002. Final Ammonium Perfluorooctanoate (C8) Assessment pf Toxicity Team (CATT) Report. https://dep.wv.gov/WWE/watershed/wqmonitoring/Documents/C-8/C-8_FINAL_CATT_REPORT_8-02.pdf.

WV DEP. 2015. Statement of Basis. DuPont Washington Works. EPA ID No. WVD 04-587-5391: West Virginia Department of Environmental Protection. https://www.dep.wv.gov/dlr/oer/superfund/Documents/DuPont_WW_Statement_Of_Basis_Apr_28_2015.pdf.

WV University. 2008. The C8 Health Project. Population Results for C8 and C8 Sulfonate Plasma Concentrations. West Virginia University. http://www.hsc.wvu.edu/media/5354/overall-c8-c8s-results.pdf

Xia, Xinghui, Zhineng Dai, Andry Harinaina Rabearisoa, Pujun Zhao, and Xiaoman Jiang. 2015. "Comparing humic substance and protein compound effects on the bioaccumulation of perfluoroalkyl substances by Daphnia magna in water." Chemosphere 119:978-986. https://doi.org/10.1016/j.chemosphere.2014.09.034.

Xia, Xinghui, Andry Harinaina Rabearisoa, Zhineng Dai, Xiaoman Jiang, Pujun Zhao, and Haotian Wang. 2015. "Inhibition effect of Na+ and Ca2+ on the bioaccumulation of perfluoroalkyl substances by Daphnia magna in the presence of protein." Environmental Toxicology and Chemistry 34 (2):429-436. https://doi.org/10.1002/etc.2823.

Xia, Xinghui, Andry H. Rabearisoa, Xiaoman Jiang, and Zhineng Dai. 2013. "Bioaccumulation of Perfluoroalkyl Substances by Daphnia magna in Water with Different Types and Concentrations of Protein." Environmental Science & Technology 47 (19):10955-10963. 10.1021/es401442y.

Xiao, Feng. 2017. "Emerging poly- and perfluoroalkyl substances in the aquatic environment: A review of current literature." Water Research 124:482-495. https://doi.org/10.1016/j.watres.2017.07.024.

Xiao, Feng, Svetlana A. Golovko, and Mikhail Y. Golovko. 2017. "Identification of novel non-ionic, cationic, zwitterionic, and anionic polyfluoroalkyl substances using UPLC–TOF–MSE high-resolution parent ion search." Analytica Chimica

Acta 988:41-49. https://doi.org/10.1016/j.aca.2017.08.016.

Xiao, Feng, Thomas R. Halbach, Matt F. Simcik, and John S. Gulliver. 2012. “Input characterization of perfluoroalkyl substances in wastewater treatment plants: Source discrimination by exploratory data analysis.” Water Research 46 (9):3101-3109. https://doi.org/10.1016/j.watres.2012.03.027.

Xiao, Feng, Bosen Jin, Svetlana A. Golovko, Mikhail Y. Golovko, and Baoshan Xing. 2019. “Sorption and Desorption Mechanisms of Cationic and Zwitterionic Per- and Polyfluoroalkyl Substances in Natural Soils: Thermodynamics and Hysteresis.” Environmental Science & Technology 53 (20):11818-11827. https://doi.org/10.1021/acs.est.9b05379.

Xiao, Feng, Pavankumar Challa Sasi, Bin Yao, Alena Kubátová, Svetlana A. Golovko, Mikhail Y. Golovko, and Dana Soli. 2020. “Thermal Stability and Decomposition of Perfluoroalkyl Substances on Spent Granular Activated Carbon.” Environmental Science & Technology Letters 7 (5):343-350. 10.1021/acs.estlett.0c00114.

Xiao, Feng, Matt F. Simcik, and John S. Gulliver. 2012. “Perfluoroalkyl acids in urban stormwater runoff: Influence of land use.” Water Research 46 (20):6601-6608. https://doi.org/10.1016/j.watres.2011.11.029.

Xiao, Feng, Matt F. Simcik, Thomas R. Halbach, and John S. Gulliver. 2015. “Perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) in soils and groundwater of a U.S. metropolitan area: Migration and implications for human exposure.” Water Research 72:64-74. https://doi.org/10.1016/j.watres.2014.09.052.

Xiao, Hanshuang, Baoying Lv, Guohua Zhao, Yujing Wang, Mingfang Li, and Dongming Li. 2011. “Hydrothermally Enhanced Electrochemical Oxidation of High Concentration Refractory Perfluorooctanoic Acid.” The Journal of Physical Chemistry A 115 (47):13836-13841. 10.1021/jp207519j.

Xiao, Leilei, Yuhan Ling, Alaaeddin Alsbaiee, Chenjun Li, Damian E. Helbling, and William R. Dichtel. 2017. “β-Cyclodextrin Polymer Network Sequesters Perfluorooctanoic Acid at Environmentally Relevant Concentrations.” Journal of the American Chemical Society 139 (23):7689-7692. 10.1021/jacs.7b02381.

Xiao, Xin, Bridget A. Ulrich, Baoliang Chen, and Christopher P. Higgins. 2017. “Sorption of Poly- and Perfluoroalkyl Substances (PFASs) Relevant to Aqueous Film-Forming Foam (AFFF)-Impacted Groundwater by Biochars and Activated Carbon.” Environmental Science & Technology 51 (11):6342-6351. 10.1021/acs.est.7b00970.

Xie, Shuangwei, Tieyu Wang, Shijie Liu, Kevin C. Jones, Andrew J. Sweetman, and Yonglong Lu. 2013. “Industrial source identification and emission estimation of perfluorooctane sulfonate in China.” Environment International 52:1-8. https://doi.org/10.1016/j.envint.2012.11.004.

Xie, Zhiyong, Zhen Wang, Olivier Magand, Alban Thollot, Ralf Ebinghaus, Wenying Mi, and Aurelien Dommergue. 2020. “Occurrence of legacy and emerging organic contaminants in snow at Dome C in the Antarctic.” Science of The Total Environment 741:140200. https://doi.org/10.1016/j.scitotenv.2020.140200.

Xie, Z., Z. Zhao, A. Moller, H. Wolschke, L. Ahrens, R. Sturm, and R. Ebinghaus. 2013. “Neutral poly- and perfluoroalkyl substances in air and seawater of the North Sea.” Environ Sci Pollut Res Int 20 (11):7988-8000. 10.1007/s11356-013-1757-z.

Xin, Yan, Xiao-Min Ren, Bin Wan, and Liang-Hong Guo. 2019. “Comparative in Vitro and in Vivo Evaluation of the Estrogenic Effect of Hexafluoropropylene Oxide Homologues.” Environmental Science & Technology 53 (14):8371-8380. 10.1021/acs.est.9b01579.

Xu, Bentuo, Mohammad Boshir Ahmed, John L. Zhou, Ali Altaee, Minghong Wu, and Gang Xu. 2017. “Photocatalytic removal of perfluoroalkyl substances from water and wastewater: Mechanism, kinetics and controlling factors.” Chemosphere 189:717-729. https://doi.org/10.1016/j.chemosphere.2017.09.110.

Xu, Bentuo, Shuai Liu, John L. Zhou, Chunmiao Zheng, Jin Weifeng, Bei Chen, Ting Zhang, and Wenhui Qiu. 2021. “PFAS and their substitutes in groundwater: Occurrence, transformation and remediation.” Journal of Hazardous Materials 412:125159. https://doi.org/10.1016/j.jhazmat.2021.125159.

Xu, Chenye, Shanshan Yin, Yingxue Liu, Fangfang Chen, Zhehui Zhong, Fang Li, Kai Liu, and Weiping Liu. 2019. “Prenatal exposure to chlorinated polyfluoroalkyl ether sulfonic acids and perfluoroalkyl acids: Potential role of maternal determinants and associations with birth outcomes.” Journal of Hazardous Materials 380:120867.

https://doi.org/10.1016/j.jhazmat.2019.120867.

Xu, D., C. Li, Y. Wen, and W. Liu. 2013. “Antioxidant defense system responses and DNA damage of earthworms exposed to perfluorooctane sulfonate (PFOS).” Environ Pollut 174:121-7. 10.1016/j.envpol.2012.10.030.

Xu, Tianyuan, Haodong Ji, Yu Gu, Tianyi Tong, Yabei Xia, Lizhi Zhang, and Dongye Zhao. 2020. “Enhanced adsorption and photocatalytic degradation of perfluorooctanoic acid in water using iron (hydr)oxides/carbon sphere composite.” Chemical Engineering Journal 388:124230. https://doi.org/10.1016/j.cej.2020.124230.

Xu, Y., E. Hansson, E. M. Andersson, K. Jakobsson, and H. Li. 2023. “High exposure to perfluoroalkyl substances in drinking water is associated with increased risk of osteoporotic fractures – A cohort study from Ronneby, Sweden.” Environ Res 217:114796. 10.1016/j.envres.2022.114796.

Xu, Y., Y. Li, K. Scott, C. H. Lindh, K. Jakobsson, T. Fletcher, B. Ohlsson, and E. M. Andersson. 2020. “Inflammatory bowel disease and biomarkers of gut inflammation and permeability in a community with high exposure to perfluoroalkyl substances through drinking water.” Environ Res 181:108923. 10.1016/j.envres.2019.108923.

Xu, Y., Y. Li, K. Scott, C. H. Lindh, K. Jakobsson, T. Fletcher, B. Ohlsson, and E. M. Andersson. 2020. “Inflammatory bowel disease and biomarkers of gut inflammation and permeability in a community with high exposure to perfluoroalkyl substances through drinking water.” Environ Res 181:108923. 10.1016/j.envres.2019.108923.

Xu, Y., C. Nielsen, Y. Li, S. Hammarstrand, E. M. Andersson, H. Li, D. S. Olsson, K. Engström, D. Pineda, C. H. Lindh, T. Fletcher, and K. Jakobsson. 2021. “Serum perfluoroalkyl substances in residents following long-term drinking water contamination from firefighting foam in Ronneby, Sweden.” Environ Int 147:106333. 10.1016/j.envint.2020.106333.

Yahia, D., M. A. El-Nasser, M. Abedel-Latif, C. Tsukuba, M. Yoshida, I. Sato, and S. Tsuda. 2010. “Effects of perfluorooctanoic acid (PFOA) exposure to pregnant mice on reproduction.” J Toxicol Sci 35 (4):527-33.

Yahia, D., C. Tsukuba, M. Yoshida, I. Sato, and S. Tsuda. 2008. “Neonatal death of mice treated with perfluorooctane sulfonate.” J Toxicol Sci 33:219-226.

Yamada, Ami, Nawel Bemrah, Bruno Veyrand, Charles Pollono, Mathilde Merlo, Virginie Desvignes, Véronique Sirot, Marine Oseredczuk, Philippe Marchand, Ronan Cariou, Jean-Phillippe Antignac, Bruno Le Bizec, and Jean-Charles Leblanc. 2014. “Perfluoroalkyl Acid Contamination and Polyunsaturated Fatty Acid Composition of French Freshwater and Marine Fishes.” Journal of Agricultural and Food Chemistry 62 (30):7593-7603. 10.1021/jf501113j.

Yamada, Takahiro, Philip H. Taylor, Robert C. Buck, Mary A. Kaiser, and Robert J. Giraud. 2005. “Thermal degradation of fluorotelomer treated articles and related materials.” Chemosphere 61 (7):974-984. https://doi.org/10.1016/j.chemosphere.2005.03.025.

Yamashita, N., K. Kannan, S. Taniyasu, Y. Horii, G. Petrick, and T. Gamo. 2005. “A global survey of perfluorinated acids in oceans.” Mar Pollut Bull 51 (8-12):658-68. 10.1016/j.marpolbul.2005.04.026.

Yamazaki, Eriko, Sachi Taniyasu, Xinhong Wang, and Nobuyoshi Yamashita. 2021. “Per- and polyfluoroalkyl substances in surface water, gas and particle in open ocean and coastal environment.” Chemosphere 272:129869. https://doi.org/10.1016/j.chemosphere.2021.129869.

Yan, Bei, Gabriel Munoz, Sébastien Sauvé, and Jinxia Liu. 2020. “Molecular mechanisms of per- and polyfluoroalkyl substances on a modified clay: a combined experimental and molecular simulation study.” Water Research 184:116166. https://doi.org/10.1016/j.watres.2020.116166.

Yan, Bei, Jian Wang, and Jinxia Liu. 2021. “STXM-XANES and computational investigations of adsorption of per- and polyfluoroalkyl substances on modified clay.” Water Research 201:117371. https://doi.org/10.1016/j.watres.2021.117371.

Yan, Hong, Ian T. Cousins, Chaojie Zhang, and Qi Zhou. 2015. “Perfluoroalkyl acids in municipal landfill leachates from China: Occurrence, fate during leachate treatment and potential impact on groundwater.” Science of The Total Environment 524-525:23-31. https://doi.org/10.1016/j.scitotenv.2015.03.111.

Yan, Peng-Fei, Sheng Dong, Katherine E. Manz, Chen Liu, Matthew J. Woodcock, Melissa P. Mezzari, Linda M. Abriola, Kurt

D. Pennell, and Natalie L. Cápiro. 2022. “Biotransformation of 8:2 Fluorotelomer Alcohol in Soil from Aqueous Film-Forming Foams (AFFFs)-Impacted Sites under Nitrate-, Sulfate-, and Iron-Reducing Conditions.” Environmental Science & Technology 56 (19):13728-13739. 10.1021/acs.est.2c03669.

Yan, Shengmin, Jianshe Wang, Wei Zhang, and Jiayin Dai. 2014. “Circulating microRNA profiles altered in mice after 28d exposure to perfluorooctanoic acid.” Toxicology Letters 224 (1):24-31. https://doi.org/10.1016/j.toxlet.2013.10.017.

Yan, Z., J. Wu, X. Wang, and Y. Zhang. 2015. “Development of Water Quality Criteria for Toxic Organic Pollutants.” In Toxic Pollutants in China, edited by Z. Yan and Z. Liu, SpringerBriefs in Environmental Science. Springer, Dordrecht. ISBN No. 978-94-017-9795-5.

Yan, Zhen-Guang, Jiang-Yue Wu, Xiao-nan Wang, and Ya-hui Zhang. 2015. “Development of Water Quality Criteria for Toxic Organic Pollutants.”1-55. 10.1007/978-94-017-9795-5_1.

Yang, Bo, Yanni Han, Yunpan Deng, Yingying Li, Qiongfang Zhuo, and Jinhua Wu. 2016. “Highly efficient removal of perfluorooctanoic acid from aqueous solution by H2O2-enhanced electrocoagulation-electroflotation technique.” Emerging Contaminants 2 (1):49-55. https://doi.org/10.1016/j.emcon.2016.04.001.

Yang, Bei, Weiying Zou, Zhenzhen Hu, Fangming Liu, Ling Zhou, Shulong Yang, Haibin Kuang, Lei Wu, Jie Wei, Jinglei Wang, Ting Zou, and Dalei Zhang. 2014. “Involvement of oxidative stress and inflammation in liver injury caused by perfluorooctanoic acid exposure in mice.” BioMed research international 2014:409837-409837. 10.1155/2014/409837.

Yang, C. H., K. P. Glover, and X. Han. 2010. “Characterization of cellular uptake of perfluorooctanoate via organic anion-transporting polypeptide 1A2, organic anion transporter 4, and urate transporter 1 for their potential roles in mediating human renal reabsorption of perfluorocarboxylates.” Toxicol Sci 117 (2):294-302. 10.1093/toxsci/kfq219.

Yang, Liping, Shengyan Tian, Lingyan Zhu, Zhengtao Liu, and Yahui Zhang. 2012. “Bioaccumulation and distribution of perfloroalkyl acids in seafood products from Bohai Bay, China.” Environmental Toxicology and Chemistry 31 (9):1972-1979. 10.1002/etc.1917.

Yang, Lin, Zhen Wang, Yu Shi, Jingguang Li, Yuxin Wang, Yunfeng Zhao, Yongning Wu, and Zongwei Cai. 2016. “Human placental transfer of perfluoroalkyl acid precursors: Levels and profiles in paired maternal and cord serum.” Chemosphere 144:1631-1638. https://doi.org/10.1016/j.chemosphere.2015.10.063.

Yang, Qian, Manuchehr Abedi-Valugerdi, Yi Xie, Xiao-Yan Zhao, Göran Möller, B. Dean Nelson, and Joseph W. DePierre. 2002. “Potent suppression of the adaptive immune response in mice upon dietary exposure to the potent peroxisome proliferator, perfluorooctanoic acid.” International Immunopharmacology 2 (2):389-397. https://doi.org/10.1016/S1567-5769(01)00164-3.

Yang, Q., Y. Xie, S. E. Alexson, B. D. Nelson, and J. W. DePierre. 2002. “Involvement of the peroxisome proliferator-activated receptor alpha in the immunomodulation caused by peroxisome proliferators in mice.” Biochem Pharmacol 63 (10):1893-900.

Yang, Q., Y. Xie, and J. W. Depierre. 2000. “Effects of peroxisome proliferators on the thymus and spleen of mice.” Clin Exp Immunol 122 (2):219-26. 10.1046/j.1365-2249.2000.01367.x.

Yang, S., J. Cheng, J. Sun, Y. Hu, and X. Liang. 2013. “Defluorination of aqueous perfluorooctanesulfonate by activated persulfate oxidation.” PLoS One 8 (10):e74877. 10.1371/journal.pone.0074877.

Yang, Suwen, Fanfan Xu, Fengchang Wu, Shengrui Wang, and Binghui Zheng. 2013. “Development of PFOS and PFOA criteria for the protection of freshwater aquatic life in China.” Science of The Total Environment 470-471:677-683. https://doi.org/10.1016/j.scitotenv.2013.09.094.

Yang, Suwen, Fanfan Xu, Fengchang Wu, Shengrui Wang, and Binghui Zheng. 2014. “Development of PFOS and PFOA criteria for the protection of freshwater aquatic life in China.” Science of The Total Environment 470-471:677-683. https://doi.org/10.1016/j.scitotenv.2013.09.094.

Yang, Y., Y. I. Cho, and A. Fridman. 2012. Plasma Discharge in Liquid: Water Treatment and Applications. Boca Raton, FL: CRC Press. ISBN No. 9781138074958.

Yang, Yuanyuan, Sisi Liu, Runmei Wang, Cailin Li, Jianhui Tang, Tao Chen, Guang-Guo Ying, and Chang-Er Chen. 2022. "Diffusive gradients in thin films (DGT) probe for effectively sampling of per- and polyfluoroalkyl substances in waters and sediments." Journal of Environmental Sciences 121:90-97. https://doi.org/10.1016/j.jes.2021.09.003.

Yao, Jingzhi, Yitao Pan, Nan Sheng, Zhaoben Su, Yong Guo, Jianshe Wang, and Jiayin Dai. 2020. "Novel Perfluoroalkyl Ether Carboxylic Acids (PFECAs) and Sulfonic Acids (PFESAs): Occurrence and Association with Serum Biochemical Parameters in Residents Living Near a Fluorochemical Plant in China." Environmental Science & Technology 54 (21):13389-13398. 10.1021/acs.est.0c02888.

Yao, Yiming, Hongkai Zhu, Bing Li, Hongwei Hu, Tao Zhang, Eriko Yamazaki, Sachi Taniyasu, Nobuyoshi Yamashita, and Hongwen Sun. 2014. "Distribution and primary source analysis of per- and poly-fluoroalkyl substances with different chain lengths in surface and groundwater in two cities, North China." Ecotoxicology and Environmental Safety 108:318-328. https://doi.org/10.1016/j.ecoenv.2014.07.021.

Yarwood, Greg, Susan Kemball-Cook, Michael Keinath, Robert L. Waterland, Stephen H. Korzeniowski, Robert C. Buck, Mark H. Russell, and Stephen T. Washburn. 2007. "High-Resolution Atmospheric Modeling of Fluorotelomer Alcohols and Perfluorocarboxylic Acids in the North American Troposphere." Environmental Science & Technology 41 (16):5756-5762. 10.1021/es0708971.

Yasuoka, K., K. Sasaki, and R. Hayashi. 2011. "An Energy-efficient process for decomposing perfluorooctanoic and perfluorooctane sulfonic acids using DC plasmas generated within gas bubbles." Plasma Sources Science and Technology 20 (3):034009. https://doi.org/10.1088/0963-0252/20/3/034009.

Yates, Brian, Ramona Darlington, Radek Zboril, and Virender Sharma. 2014. "High-valent iron-based oxidants to treat perfluorooctanesulfonate and perfluorooctanoic acid in water." Environmental Chemistry Letters 12:413-417. 10.1007/s10311-014-0463-5.

Ye, X., K. Kato, L. Y. Wong, T. Jia, A. Kalathil, J. Latremouille, and A. M. Calafat. 2018. "Per- and polyfluoroalkyl substances in sera from children 3 to 11 years of age participating in the National Health and Nutrition Examination Survey 2013-2014." Int J Hyg Environ Health 221 (1):9-16. 10.1016/j.ijheh.2017.09.011.

Yeung, L. W., A. O. De Silva, E. I. Loi, C. H. Marvin, S. Taniyasu, N. Yamashita, S. A. Mabury, D. C. Muir, and P. K. Lam. 2013. "Perfluoroalkyl substances and extractable organic fluorine in surface sediments and cores from Lake Ontario." Environ Int 59:389-97. 10.1016/j.envint.2013.06.026.

Yeung, L. W., S. J. Robinson, J. Koschorreck, and S. A. Mabury. 2013. "Part I. A temporal study of PFCAs and their precursors in human plasma from two German cities 1982-2009." Environ Sci Technol 47 (8):3865-74. 10.1021/es303716k.

Yeung, Leo W. Y., Clifton Dassuncao, Scott Mabury, Elsie M. Sunderland, Xianming Zhang, and Rainer Lohmann. 2017. "Vertical Profiles, Sources, and Transport of PFASs in the Arctic Ocean." Environmental Science & Technology 51 (12):6735-6744. 10.1021/acs.est.7b00788.

Yeung, Leo W. Y., and Scott A. Mabury. 2016. "Are humans exposed to increasing amounts of unidentified organofluorine?" Environmental Chemistry 13 (1):102-110.

Yeung, Leo W. Y., Yuichi Miyake, Sachi Taniyasu, Yuan Wang, Hongxia Yu, M. K. So, Guibin Jiang, Yongning Wu, Jingguang Li, John P. Giesy, Nobuyoshi Yamashita, and Paul K. S. Lam. 2008. "Perfluorinated Compounds and Total and Extractable Organic Fluorine in Human Blood Samples from China." Environmental Science & Technology 42 (21):8140-8145. 10.1021/es800631n.

Yi, L. B., L. Y. Chai, Y. Xie, Q. J. Peng, and Q. Z. Peng. 2016. "Isolation, identification, and degradation performance of a PFOA-degrading strain." Genet Mol Res 15 (2). 10.4238/gmr.15028043.

Yi, Shan, Katie C. Harding-Marjanovic, Erika F. Houtz, Edmund Antell, Christopher Olivares, Rita V. Nichiporuk, Anthony T. Iavarone, Wei-Qin Zhuang, Jennifer A. Field, David L. Sedlak, and Lisa Alvarez-Cohen. 2022. "Biotransformation of 6:2 Fluorotelomer Thioether Amido Sulfonate in Aqueous Film-Forming Foams under Nitrate-Reducing Conditions." Environmental Science & Technology 56 (15):10646-10655. 10.1021/acs.est.2c00063.

Yi, Shan, Katie C. Harding-Marjanovic, Erika F. Houtz, Ying Gao, Jennifer E. Lawrence, Rita V. Nichiporuk, Anthony T.

Iavarone, Wei-Qin Zhuang, Martin Hansen, Jennifer A. Field, David L. Sedlak, and Lisa Alvarez-Cohen. 2018. “Biotransformation of AFFF Component 6:2 Fluorotelomer Thioether Amido Sulfonate Generates 6:2 Fluorotelomer Thioether Carboxylate under Sulfate-Reducing Conditions.” Environmental Science & Technology Letters 5 (5):283-288. 10.1021/acs.estlett.8b00148.

Yin, P., Z. Hu, X. Song, J. Liu, and N. Lin. 2016. “Activated Persulfate Oxidation of Perfluorooctanoic Acid (PFOA) in Groundwater under Acidic Conditions.” Int J Environ Res Public Health 13 (6). 10.3390/ijerph13060602.

Yoo, Hoon, John W. Washington, J. Jackson Ellington, Thomas M. Jenkins, and Michael P. Neill. 2010. “Concentrations, Distribution, and Persistence of Fluorotelomer Alcohols in Sludge-Applied Soils near Decatur, Alabama, USA.” Environmental Science & Technology 44 (22):8397-8402. 10.1021/es100390r.

Yoo, Hoon, John W. Washington, Thomas M. Jenkins, and J. Jackson Ellington. 2011. “Quantitative Determination of Perfluorochemicals and Fluorotelomer Alcohols in Plants from Biosolid-Amended Fields using LC/MS/MS and GC/MS.” Environmental Science & Technology 45 (19):7985-7990. https://doi.org/10.1021/es102972m.

Yoo, Hoon, John W. Washington, Thomas M. Jenkins, and E. Laurence Libelo. 2009. “Analysis of perfluorinated chemicals in sludge: Method development and initial results.” Journal of Chromatography A 1216 (45):7831-7839. https://doi.org/10.1016/j.chroma.2009.09.051.

Young, Anna S., Russ Hauser, Tamarra M. James-Todd, Brent A. Coull, Hongkai Zhu, Kurunthachalam Kannan, Aaron J. Specht, Maya S. Bliss, and Joseph G. Allen. 2021. “Impact of “healthier” materials interventions on dust concentrations of per- and polyfluoroalkyl substances, polybrominated diphenyl ethers, and organophosphate esters.” Environment International 150:106151. https://doi.org/10.1016/j.envint.2020.106151.

Young, C. J., and S. A. Mabury. 2010. “Atmospheric perfluorinated acid precursors: chemistry, occurrence, and impacts.” Rev Environ Contam Toxicol 208:1-109. 10.1007/978-1-4419-6880-7_1.

Yu, Nanyang, Haozhe Wen, Xuebing Wang, Eriko Yamazaki, Sachi Taniyasu, Nobuyoshi Yamashita, Hongxia Yu, and Si Wei. 2020. “Nontarget Discovery of Per- and Polyfluoroalkyl Substances in Atmospheric Particulate Matter and Gaseous Phase Using Cryogenic Air Sampler.” Environmental Science & Technology 54 (6):3103-3113. 10.1021/acs.est.9b05457.

Yu, Qiang, Ruiqi Zhang, Shubo Deng, Jun Huang, and Gang Yu. 2009. “Sorption of perfluorooctane sulfonate and perfluorooctanoate on activated carbons and resin: Kinetic and isotherm study.” Water Research 43 (4):1150-1158. https://doi.org/10.1016/j.watres.2008.12.001.

Yu, W. G., W. Liu, and Y. H. Jin. 2009. “Effects of perfluorooctane sulfonate on rat thyroid hormone biosynthesis and metabolism.” Environ Toxicol Chem 28 (5):990-6. 10.1897/08-345.1.

Yuan, Guanxiang, Hui Peng, Chong Huang, and Jianying Hu. 2016. “Ubiquitous Occurrence of Fluorotelomer Alcohols in Eco-Friendly Paper-Made Food-Contact Materials and Their Implication for Human Exposure.” Environmental Science & Technology 50 (2):942-950. https://doi.org/10.1021/acs.est.5b03806.

Zabaleta, I., E. Bizkarguenaga, U. Izagirre, N. Negreira, A. Covaci, J. P. Benskin, A. Prieto, and O. Zuloaga. 2017. “Biotransformation of 8:2 polyfluoroalkyl phosphate diester in gilthead bream (Sparus aurata).” Sci Total Environ 609:1085-1092. 10.1016/j.scitotenv.2017.07.241.

Zabaleta, Itsaso, Ekhine Bizkarguenaga, Deborah B. O. Nunoo, Lara Schultes, Juliana Leonel, Ailette Prieto, Olatz Zuloaga, and Jonathan P. Benskin. 2018. “Biodegradation and Uptake of the Pesticide Sulfluramid in a Soil–Carrot Mesocosm.” Environmental Science & Technology 52 (5):2603-2611. 10.1021/acs.est.7b03876.

Zaggia, Alessandro, and Bruno Ameduri. 2012. “Recent advances on synthesis of potentially non-bioaccumulable fluorinated surfactants.” Current Opinion in Colloid & Interface Science 17 (4):188-195. https://doi.org/10.1016/j.cocis.2012.04.001.

Zaggia, A., L. Conte, L. Falletti, M. Fant, and A. Chiorboli. 2016. “Use of strong anion exchange resins for the removal of perfluoroalkylated substances from contaminated drinking water in batch and continuous pilot plants.” Water Res 91:137-46. 10.1016/j.watres.2015.12.039.

Zareitalabad, P., J. Siemens, M. Hamer, and W. Amelung. 2013. “Perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) in surface waters, sediments, soils and wastewater – A review on concentrations and distribution coefficients.” Chemosphere 91 (6):725-732. https://doi.org/10.1016/j.chemosphere.2013.02.024.

Zareitalabad, Parva, Jan Siemens, Florian Wichern, Wulf Amelung, and Rainer Georg Joergensen. 2013. “Dose-dependent reactions of Aporrectodea caliginosa to perfluorooctanoic acid and perfluorooctanesulfonic acid in soil.” Ecotoxicology and Environmental Safety 95:39-43. https://doi.org/10.1016/j.ecoenv.2013.05.012.

Zeilmaker, M. J., S. Fraki, E. M. J. Verbruggen, and B. G. H. NBokkers. 2018. Mixture exposure to PFAS: A relative Potency Factor approach. RIVM Report 2018-0070. The Netherlands: Welfare and Sport National Institute for Public Health and the Environment. Ministry of Health. https://www.rivm.nl/bibliotheek/rapporten/2018-0070.pdf.

Zembouai, Idris, Mustapha Kaci, Stéphane Bruzaud, Isabelle Pillin, Jean-Luc Audic, Shima Shayanfar, and Suresh D. Pillai. 2016. “Electron beam radiation effects on properties and ecotoxicity of PHBV/PLA blends in presence of organo-modified montmorillonite.” Polymer Degradation and Stability 132:117-126. https://doi.org/10.1016/j.polymdegradstab.2016.03.019.

Zeng, Chao, Ariel Atkinson, Naushita Sharma, Harsh Ashani, Annika Hjelmstad, Krishishvar Venkatesh, and Paul Westerhoff. 2020. “Removing per- and polyfluoroalkyl substances from groundwaters using activated carbon and ion exchange resin packed columns.” AWWA Water Science 2 (1):e1172. https://doi.org/10.1002/aws2.1172.

Zeng, Chao, Ariel Atkinson, Naushita Sharma, Harsh Ashani, Annika Hjelmstad, Krishishvar Venkatesh, and Paul Westerhoff. 2020. “Removing per- and polyfluoroalkyl substances from groundwaters using activated carbon and ion exchange resin packed columns.” AWWA Water Science 2 (1):e1172. https://doi.org/10.1002/aws2.1172.

Zeng, H. C., L. Zhang, Y. Y. Li, Y. J. Wang, W. Xia, Y. Lin, J. Wei, and S. Q. Xu. 2011. “Inflammation-like glial response in rat brain induced by prenatal PFOS exposure.” Neurotoxicology 32 (1):130-9. 10.1016/j.neuro.2010.10.001.

Zeng, Jicai, and Bo Guo. 2021. “Multidimensional simulation of PFAS transport and leaching in the vadose zone: Impact of surfactant-induced flow and subsurface heterogeneities.” Advances in Water Resources 155:104015. https://doi.org/10.1016/j.advwatres.2021.104015.

Zenobio, Jenny E., Mahsa Modiri-Gharehveran, Chloe de Perre, Chad D. Vecitis, and Linda S. Lee. 2020. “Reductive transformation of perfluorooctanesulfonate by nNiFe0-Activated carbon.” Journal of Hazardous Materials 397:122782. https://doi.org/10.1016/j.jhazmat.2020.122782.

Zenobio, Jenny E., Omobayo A. Salawu, Ziwei Han, and Adeyemi S. Adeleye. 2022. “Adsorption of per- and polyfluoroalkyl substances (PFAS) to containers.” Journal of Hazardous Materials Advances 7:100130. https://doi.org/10.1016/j.hazadv.2022.100130.

Zhang, Chuhui, Zachary R. Hopkins, James McCord, Mark J. Strynar, and Detlef R. U. Knappe. 2019. “Fate of Per- and Polyfluoroalkyl Ether Acids in the Total Oxidizable Precursor Assay and Implications for the Analysis of Impacted Water.” Environmental Science & Technology Letters 6 (11):662-668. https://doi.org/10.1021/acs.estlett.9b00525.

Zhang, Chaojie, Yan Qu, Xiaoyun Zhao, and Qi Zhou. 2015. “Photoinduced Reductive Decomposition of Perflurooctanoic Acid in Water: Effect of Temperature and Ionic Strength.” CLEAN – Soil, Air, Water 43 (2):223-228. 10.1002/clen.201300869.

Zhang, Dongqing, Weilan Zhang, and Yanna Liang. 2019. “Distribution of eight perfluoroalkyl acids in plant-soil-water systems and their effect on the soil microbial community.” Science of The Total Environment 697:134146. https://doi.org/10.1016/j.scitotenv.2019.134146.

Zhang, D. Q., W. L. Zhang, and Y. N. Liang. 2019. “Adsorption of perfluoroalkyl and polyfluoroalkyl substances (PFASs) from aqueous solution – A review.” Science of The Total Environment 694:133606. https://doi.org/10.1016/j.scitotenv.2019.133606.

Zhang, H., W. Liu, X. He, Y. Wang, and Q. Zhang. 2015. “Uptake of perfluoroalkyl acids in the leaves of coniferous and deciduous broad-leaved trees.” Environ Toxicol Chem 34 (7):1499-504. 10.1002/etc.2968.

Zhang, H., Y. Lu, B. Luo, S. Yan, X. Guo, and J. Dai. 2014. “Proteomic analysis of mouse testis reveals perfluorooctanoic acid-induced reproductive dysfunction via direct disturbance of testicular steroidogenic machinery.” J Proteome Res 13 (7):3370-85. 10.1021/pr500228d.

Zhang, Hongxia, Xiujuan Zhou, Nan Sheng, Ruina Cui, Qianqian Cui, Hua Guo, Yong Guo, Yan Sun, and Jiayin Dai. 2018. “Subchronic Hepatotoxicity Effects of 6:2 Chlorinated Polyfluorinated Ether Sulfonate (6:2 Cl-PFESA), a Novel Perfluorooctanesulfonate (PFOS) Alternative, on Adult Male Mice.” Environmental Science & Technology 52 (21):12809-12818. 10.1021/acs.est.8b04368.

Zhang, L., L. S. Lee, J. Niu, and J. Liu. 2017. “Kinetic analysis of aerobic biotransformation pathways of a perfluorooctane sulfonate (PFOS) precursor in distinctly different soils.” Environ Pollut 229:159-167. 10.1016/j.envpol.2017.05.074.

Zhang, Lianying, Xiao-Min Ren, and Liang-Hong Guo. 2013. “Structure-Based Investigation on the Interaction of Perfluorinated Compounds with Human Liver Fatty Acid Binding Protein.” Environmental Science & Technology 47 (19):11293-11301. 10.1021/es4026722.

Zhang, Lu, Hongwen Sun, Qi Wang, Hao Chen, Yiming Yao, Zhen Zhao, and Alfredo C. Alder. 2019. “Uptake mechanisms of perfluoroalkyl acids with different carbon chain lengths (C2-C8) by wheat (Triticum acstivnm L.).” Science of The Total Environment 654:19-27. https://doi.org/10.1016/j.scitotenv.2018.10.443.

Zhang, Mengke, Kyle Yamada, Stephen Bourguet, Jennifer Guelfo, and Eric M. Suuberg. 2020. “Vapor Pressure of Nine Perfluoroalkyl Substances (PFASs) Determined Using the Knudsen Effusion Method.” Journal of Chemical & Engineering Data 65 (5):2332-2342. https://doi.org/10.1021/acs.jced.9b00922.

Zhang, Ruiming, Wei Yan, and Chuanyong Jing. 2015. “Experimental and molecular dynamic simulation study of perfluorooctane sulfonate adsorption on soil and sediment components.” Journal of Environmental Sciences 29:131-138. https://doi.org/10.1016/j.jes.2014.11.001.

Zhang, Shu, Bogdan Szostek, Patricia K. McCausland, Barry W. Wolstenholme, Xiaoxia Lu, Ning Wang, and Robert C. Buck. 2013. “6:2 and 8:2 Fluorotelomer Alcohol Anaerobic Biotransformation in Digester Sludge from a WWTP under Methanogenic Conditions.” Environmental Science & Technology 47 (9):4227-4235. https://doi.org/10.1021/es4000824.

Zhang, T., G. Pan, and Q. Zhou. 2016. “Temperature effect on photolysis decomposing of perfluorooctanoic acid.” J Environ Sci (China) 42:126-133. 10.1016/j.jes.2015.05.008.

Zhang, T., H. Sun, Y. Lin, X. Qin, Y. Zhang, X. Geng, and K. Kannan. 2013. “Distribution of poly- and perfluoroalkyl substances in matched samples from pregnant women and carbon chain length related maternal transfer.” Environ Sci Technol 47 (14):7974-81. 10.1021/es400937y.

Zhang, Weilan, and Yanna Liang. 2022. “Performance of different sorbents toward stabilizing per- and polyfluoroalkyl substances (PFAS) in soil.” Environmental Advances 8:100217. https://doi.org/10.1016/j.envadv.2022.100217.

Zhang, Weilan, Dongqing Zhang, and Yanna Liang. 2019. “Nanotechnology in remediation of water contaminated by poly- and perfluoroalkyl substances: A review.” Environmental Pollution 247:266-276. https://doi.org/10.1016/j.envpol.2019.01.045.

Zhang, W., Y. Zhang, H. Zhang, J. Wang, R. Cui, and J. Dai. 2012. “Sex differences in transcriptional expression of FABPs in zebrafish liver after chronic perfluorononanoic acid exposure.” Environmental Science and Technology 46 (9):5175-5182. 10.1021/es300147w.

Zhang, Xianming, Trevor N. Brown, Frank Wania, Eldbjørg S. Heimstad, and Kai-Uwe Goss. 2010. “Assessment of chemical screening outcomes based on different partitioning property estimation methods.” Environment International 36 (6):514-520. https://doi.org/10.1016/j.envint.2010.03.010.

Zhang, Xianming, Rainer Lohmann, Clifton Dassuncao, Xindi C. Hu, Andrea K. Weber, Chad D. Vecitis, and Elsie M. Sunderland. 2016. “Source Attribution of Poly- and Perfluoroalkyl Substances (PFASs) in Surface Waters from Rhode Island and the New York Metropolitan Area.” Environmental Science & Technology Letters 3 (9):316-321. https://doi.org/10.1021/acs.estlett.6b00255.

Zhang, Y., S. Beesoon, L. Zhu, and J. W. Martin. 2013. “Biomonitoring of perfluoroalkyl acids in human urine and estimates of biological half-life." Environ Sci Technol 47 (18):10619-27. 10.1021/es401905e.

Zhao, Baoxiu, Mou Lv, and Li Zhou. 2012. "Photocatalytic degradation of perfluorooctanoic acid with β-Ga2O3 in anoxic aqueous solution." Journal of Environmental Sciences 24 (4):774-780. https://doi.org/10.1016/S1001-0742(11)60818-8.

Zhao, H., C. Chen, X. Zhang, J. Chen, and X. Quan. 2011. "Phytotoxicity of PFOS and PFOA to Brassica chinensis in different Chinese soils." Ecotoxicol Environ Saf 74 (5):1343-7. 10.1016/j.ecoenv.2011.03.007.

Zhao, Hongying, Junxia Gao, Guohua Zhao, Jiaqi Fan, Yanbin Wang, and Yujing Wang. 2013. "Fabrication of novel SnO2-Sb/carbon aerogel electrode for ultrasonic electrochemical oxidation of perfluorooctanoate with high catalytic efficiency." Applied Catalysis B: Environmental 136-137:278-286. https://doi.org/10.1016/j.apcatb.2013.02.013.

Zhao, Hua-Zhang, Lei Wang, Ying-Yue Chang, and Yi Xu. 2016. "High-efficiency removal of perfluorooctanoic acid from water by covalently bound hybrid coagulants (CBHyC) bearing a hydrophobic quaternary ammonium group." Separation and Purification Technology 158:9-15. https://doi.org/10.1016/j.seppur.2015.11.044.

Zhao, Lixia, Jingna Bian, Yahui Zhang, Lingyan Zhu, and Zhengtao Liu. 2014. "Comparison of the sorption behaviors and mechanisms of perfluorosulfonates and perfluorocarboxylic acids on three kinds of clay minerals." Chemosphere 114:51-58. https://doi.org/10.1016/j.chemosphere.2014.03.098.

Zhao, Lijie, Patrick W. Folsom, Barry W. Wolstenholme, Hongwen Sun, Ning Wang, and Robert C. Buck. 2013. "6:2 Fluorotelomer alcohol biotransformation in an aerobic river sediment system." Chemosphere 90 (2):203-209. https://doi.org/10.1016/j.chemosphere.2012.06.035.

Zhao, Lijie, Patricia K. McCausland, Patrick W. Folsom, Barry W. Wolstenholme, Hongwen Sun, Ning Wang, and Robert C. Buck. 2013. "6:2 Fluorotelomer alcohol aerobic biotransformation in activated sludge from two domestic wastewater treatment plants." Chemosphere 92 (4):464-470. https://doi.org/10.1016/j.chemosphere.2013.02.032.

Zhao, Lixia, Yifeng Zhang, Shuhong Fang, Lingyan Zhu, and Zhengtao Liu. 2014. "Comparative sorption and desorption behaviors of PFHxS and PFOS on sequentially extracted humic substances." Journal of Environmental Sciences 26 (12):2517-2525. https://doi.org/10.1016/j.jes.2014.04.009.

Zhao, L., M. Zhou, T. Zhang, and H. Sun. 2013. "Polyfluorinated and perfluorinated chemicals in precipitation and runoff from cities across eastern and central China." Arch Environ Contam Toxicol 64 (2):198-207. https://doi.org/10.1007/s00244-012-9832-x.

Zhao, S., S. Fang, L. Zhu, L. Liu, Z. Liu, and Y. Zhang. 2014. "Mutual impacts of wheat (Triticum aestivum L.) and earthworms (Eisenia fetida) on the bioavailability of perfluoroalkyl substances (PFASs) in soil." Environ Pollut 184:495-501. 10.1016/j.envpol.2013.09.032.

Zhao, S., X. Ma, S. Fang, and L. Zhu. 2016. "Behaviors of N-ethyl perfluorooctane sulfonamide ethanol (N-EtFOSE) in a soil-earthworm system: Transformation and bioaccumulation." Sci Total Environ 554-555:186-91. 10.1016/j.scitotenv.2016.02.180.

Zhao, Zhen, Xianghui Cheng, Xia Hua, Bin Jiang, Chongguo Tian, Jianhui Tang, Qilu Li, Hongwen Sun, Tian Lin, Yuhong Liao, and Gan Zhang. 2020. "Emerging and legacy per- and polyfluoroalkyl substances in water, sediment, and air of the Bohai Sea and its surrounding rivers." Environmental Pollution 263:114391. https://doi.org/10.1016/j.envpol.2020.114391.

Zhao, Zhen, Jianhui Tang, Lijie Mi, Chongguo Tian, Guangcai Zhong, Gan Zhang, Shaorui Wang, Qilu Li, Ralf Ebinghaus, Zhiyong Xie, and Hongwen Sun. 2017. "Perfluoroalkyl and polyfluoroalkyl substances in the lower atmosphere and surface waters of the Chinese Bohai Sea, Yellow Sea, and Yangtze River estuary." Science of The Total Environment 599-600:114-123. https://doi.org/10.1016/j.scitotenv.2017.04.147.

Zhao, Z., Z. Xie, A. Moller, R. Sturm, J. Tang, G. Zhang, and R. Ebinghaus. 2012. "Distribution and long-range transport of polyfluoroalkyl substances in the Arctic, Atlantic Ocean and Antarctic coast." Environ Pollut 170:71-7. 10.1016/j.envpol.2012.06.004.

Zheng, Guomao, Brandon E. Boor, Erika Schreder, and Amina Salamova. 2020. "Indoor exposure to per- and polyfluoroalkyl substances (PFAS) in the childcare environment." Environmental Pollution 258:113714. https://doi.org/10.1016/j.envpol.2019.113714.

Zheng, Guomao, Erika Schreder, Jennifer C. Dempsey, Nancy Uding, Valerie Chu, Gabriel Andres, Sheela Sathyanarayana, and Amina Salamova. 2021. "Per- and Polyfluoroalkyl Substances (PFAS) in Breast Milk: Concerning Trends for Current-Use PFAS." Environmental Science & Technology. https://doi.org/10.1021/acs.est.0c06978.

Zheng, X. M., H. L. Liu, W. Shi, S. Wei, J. P. Giesy, and H. X. Yu. 2011. "Effects of perfluorinated compounds on development of zebrafish embryos." Environ Sci Pollut Res Int 19 (7):2498-505. 10.1007/s11356-012-0977-y.

Zhi, Yue, and Jinxia Liu. 2018. "Sorption and desorption of anionic, cationic and zwitterionic polyfluoroalkyl substances by soil organic matter and pyrogenic carbonaceous materials." Chemical Engineering Journal 346:682-691. https://doi.org/10.1016/j.cej.2018.04.042.

Zhong, Wenjue, Liyuan Zhang, Yannan Cui, Meng Chen, and Lingyan Zhu. 2019. "Probing mechanisms for bioaccumulation of perfluoroalkyl acids in carp (Cyprinus carpio): Impacts of protein binding affinities and elimination pathways." Science of The Total Environment 647:992-999. https://doi.org/10.1016/j.scitotenv.2018.08.099.

Zhou, Jiaqi, Karsten Baumann, Naomi Chang, Glenn Morrison, Wanda Bodnar, Zhenfa Zhang, Joanna M. Atkin, Jason D. Surratt, and Barbara J. Turpin. 2022. "Per- and polyfluoroalkyl substances (PFASs) in airborne particulate matter (PM2.0) emitted during floor waxing: A pilot study." Atmospheric Environment 268:118845. https://doi.org/10.1016/j.atmosenv.2021.118845.

Zhou, J., K. Baumann, R. N. Mead, S. A. Skrabal, R. J. Kieber, G. B. Avery, M. Shimizu, J. C. DeWitt, M. Sun, S. A. Vance, W. Bodnar, Z. Zhang, L. B. Collins, J. D. Surratt, and B. J. Turpin. 2021. "PFOS dominates PFAS composition in ambient fine particulate matter (PM2.5) collected across North Carolina nearly 20 years after the end of its US production." Environmental Science: Processes & Impacts 23 (4):580-587. 10.1039/D0EM00497A.

Zhou, Minghua, Meiling Chi, Hongyu Wang, and Tao Jin. 2012. "Anode modification by electrochemical oxidation: A new practical method to improve the performance of microbial fuel cells." Biochemical Engineering Journal 60:151-155. https://doi.org/10.1016/j.bej.2011.10.014.

Zhou, Qin, Shubo Deng, Qiang Yu, Qiaoying Zhang, Gang Yu, Jun Huang, and Hongping He. 2010. "Sorption of perfluorooctane sulfonate on organo-montmorillonites." Chemosphere 78 (6):688-694. https://doi.org/10.1016/j.chemosphere.2009.12.005.

Zhou, Qin, Hong Ping He, Jian Xi Zhu, Wei Shen, Ray L. Frost, and Peng Yuan. 2008. "Mechanism of p-nitrophenol adsorption from aqueous solution by HDTMA+-pillared montmorillonite—Implications for water purification." Journal of Hazardous Materials 154 (1):1025-1032. https://doi.org/10.1016/j.jhazmat.2007.11.009.

Zhou, Qin, Gang Pan, and Wei Shen. 2013. "Enhanced sorption of perfluorooctane sulfonate and Cr(VI) on organo montmorillonite: influence of solution pH and uptake mechanism." Adsorption 19 (2):709-715. 10.1007/s10450-013-9496-5.

Zhou, Qin, Gang Pan, and Jun Zhang. 2013. "Effective sorption of perfluorooctane sulfonate (PFOS) on hexadecyltrimethylammonium bromide immobilized mesoporous SiO2 hollow sphere." Chemosphere 90 (9):2461-2466. https://doi.org/10.1016/j.chemosphere.2012.11.009.

Zhou, Xiujuan, Jianshe Wang, Nan Sheng, Ruina Cui, Yiqun Deng, and Jiayin Dai. 2018. "Subchronic reproductive effects of 6:2 chlorinated polyfluorinated ether sulfonate (6:2 Cl-PFAES), an alternative to PFOS, on adult male mice." Journal of Hazardous Materials 358:256-264. https://doi.org/10.1016/j.jhazmat.2018.07.004.

Zhu, Lizhong, and Baoliang Chen. 2000. "Sorption Behavior of p-Nitrophenol on the Interface between Anion−Cation Organobentonite and Water." Environmental Science & Technology 34 (14):2997-3002. 10.1021/es991460z.

Zhu, Runliang, Qingze Chen, Qing Zhou, Yunfei Xi, Jianxi Zhu, and Hongping He. 2016. "Adsorbents based on montmorillonite for contaminant removal from water: A review." Applied Clay Science 123:239-258. https://doi.org/10.1016/j.clay.2015.12.024.

Zhu, W., H. Roakes, S. G. Zemba, and A.R. Badireddy. 2019. PFAS Background in Vermont Shallow Soils. Univ. of

Vermont and Sanborn Head & Assoc. https://anrweb.vt.gov/PubDocs/DEC/PFOA/Soil-Background/PFAS-Background-Vermont-Shallow-Soils-03-24-19.pdf.

Zhuo, Qiongfang, Shubo Deng, Bo Yang, Jun Huang, Bin Wang, Tingting Zhang, and Gang Yu. 2012. “Degradation of perfluorinated compounds on a boron-doped diamond electrode.” Electrochimica Acta 77:17-22. https://doi.org/10.1016/j.electacta.2012.04.145.

Zhuo, Qiongfang, Shubo Deng, Bo Yang, Jun Huang, and Gang Yu. 2011. “Efficient Electrochemical Oxidation of Perfluorooctanoate Using a Ti/SnO2-Sb-Bi Anode.” Environmental Science & Technology 45 (7):2973-2979. 10.1021/es1024542.

Zhuo, Q., X. Li, F. Yan, B. Yang, S. Deng, J. Huang, and G. Yu. 2014. “Electrochemical oxidation of 1H,1H,2H,2H-perfluorooctane sulfonic acid (6:2 FTS) on DSA electrode: operating parameters and mechanism.” J Environ Sci (China) 26 (8):1733-9. https://doi.org/10.1016/j.jes.2014.06.014.

Ziltek. 2018. Safe Disposal of PFAS Soil from Commercial Airport in Australia. Case Study – PFAS Z088-02. Adelaide, South Australia. https://rembind.com/projects/pfas-in-soil-full-scale-project/.

Zodrow, Jeanmarie M., Meredith Frenchmeyer, Kaitlyn Dally, Erin Osborn, Paul Anderson, and Craig Divine. 2021. “Development of Per and Polyfluoroalkyl Substances Ecological Risk-Based Screening Levels.” Environmental Toxicology and Chemistry 40 (3):921-936. https://doi.org/10.1002/etc.4975.

Zushi, Y., and S. Masunaga. 2009. “Identifying the nonpoint source of perfluorinated compounds using a geographic information system-based approach.” Environ Toxicol Chem 28 (4):691-700. https://doi.org/10.1897/08-194.1.

Updated September 2023.

Acronyms

AACO	Army Aviation Centre Oakey
AA-QS	annual average quality standards
ADONA	trade name for 4,8-dioxa-3H-perfluorononanoate
AERMOD	American Meteorological Society/EPA Regulatory Model
AFCEC	Air Force Civil Engineering Center
AFFF	aqueous film-forming foam
ALT	alanine aminotransferase
amu	atomic mass unit
ANSES	French National Agency for Food Safety, Environment and Labor
ANSI	American National Standards Institute
AOF	adsorbable organic fluorine
APC	air pollution control
APFN	ammonium perfluoronanoate
APFO	ammonium perfluorooctanoate
ARAR	applicable or relevant and appropriate requirement
AM	arithmetic mean
ANPRM	Advance Notice of Proposed Rulemaking
ARP	advanced reduction processes
ATSDR	Agency for Toxic Substances and Disease Registry
AWI	Air-water interface
AWQC	ambient water quality criteria
BAF	bioaccumulation factor
BARC	bottom antireflective coatings
BAT	best available technology economically achievable
BBMD	Bayesian benchmark dose
BCF	bioconcentration factor
BERA	baseline ecological risk assessment
bgs	below ground surface
BMD	benchmark dose
BMF	biomagnification factor
BMP	best management practices
BOHP	$Bi_3O(OH)(PO_4)_2$
BSAF	biota-sediment accumulation factor
BuFASA	*N*-butyl perfluoroalkane sulfonamide
BuFASE	*N*-butyl perfluoroalkane sulfonamido ethanols
BuFASAA	*N*-butyl perfluoroalkane sulfonamido acetic acid
BV	bed volume
BW	body weight
C	carbon
C8	historical name for PFOA
C&D	construction and demolition

CAA	Clean Air Act
CAC	colloidal activated carbon
CalEPA	California Environmental Protection Agency
CAP	chemical action plan, or corrective action plan
CAPEX	capital expenses
CAS	Chemical Abstracts Service
CBPR	community-based participatory research
CCL	Contaminant Candidate List
CCV	continuing calibration verification
CDC	U.S. Centers for Disease Control and Prevention
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CHP	catalyzed hydrogen peroxide
CIC	combustion ion chromatography
CIMS	chemical ionization mass spectrometry
CL	clearance factor
ClPFPECA	chloroperfluoropolyether carboxylate
CMC	critical micelle concentrations
CNT	carbon nanotube
COOH	carboxylic acid functional group
CSF	cancer slope factor
CSM	conceptual site model
CWA	Clean Water Act
Da	Dalton (unit of mass)
DDT	dichlorodiphenyltrichloroethane
DIN EN	Deutsches Institut für Normung, German Institute for Standardization, English
DMSO	dimethyl sulfoxide
DNAPL	dense nonaqueous phase liquid
DOC	dissolved organic carbon
DQO	data quality objective
DW	drinking water
DWR	durable water repellent
EAO	emergency administrative order
EBCT	empty bed contact time
ECCC	Environment and Climate Change Canada
ECF	electrochemical fluorination
ECHA	European Chemicals Agency
ECOS	Environmental Council of the States
ECT	Emerging Compound Treatment Technologies, Inc.
EE/CA	Engineering Evaluation/Cost Analysis
EIS	extraction internal standards
ELG	effluent limitation guidelines
EPC	exposure point concentration
ERA	ecological risk assessment
ERB	equipment rinse blank
ESS	Environmental Sequence Stratigraphy
ESTCP	Environmental Security Technology Certification Program
EtFASA	*N*-ethyl perfluoroalkane sulfonamide

EtFASE	*N*-ethyl perfluoroalkane sulfonamido ethanol (var: N-ethyl perfluoroalkane sulfonamide ethanol)
EtFASAA	*N*-ethyl perfluoroalkane sulfonamido acetic acid (var: *N*-ethyl perfluoroalkane sulfonamide acetic acid)
ETFE	ethylene tetrafluoroethylene
EtFOSA	*N*-ethyl perfluorooctane sulfonamide
EtFOSE	*N*-ethyl perfluorooctane sulfonamido ethanol (var: *N*-ethyl perfluorooctane sulfonamide ethanol)
EU	European Union
F	fluorine
F-53B	chlorinated polyfluorinated ether sulfonate (PFOS substitute for plating)
F3	fluorine-free foams
FAA	Federal Aviation Administration
FAQ	frequently asked questions
FASA	perfluoroalkane sulfonamide
FASE	perfluoroalkane sulfonamido ethanol (var: perfluoroalkane sulfonamide ethanol)
FASAA	perfluoroalkane sulfonamido acetic acid (var: perfluoroalkane sulfonamide acetic acid)
FCM	food contact materials
FCS	food contact substances
FD	field duplicate
FDA	U.S. Food and Drug Administration
FEC	Foam Exposure Committee
FECA	fluorinated ether carboxylate
FEP	perfluorinated ethylene-propylene
FFFC	Fire Fighting Foam Coalition
FFFP	film-forming fluoroprotein foam
FhxSA	perfluorohexane sulfonamide
f_{oc}	fraction of organic carbon
FOSA, or PFOSA	perfluorooctane sulfonamide
FOSE	perfluorooctane sulfonamido ethanol (var: perfluorooctane sulfonamide ethanol)
FOSAA	perfluorooctane sulfonamido acetic acid (var: perfluorooctane sulfonamide acetic acid)
FP	fluoroprotein (used in the contex of firefighting foam formulations that contain a fluorinated surfactant)
FRB	field reagent blank
FRM	Federal Reference Method
FSANZ	Food Standards Australia and New Zealand
fT4	free thyroxine
FTA	fire training area
FTCA	fluorotelomer carboxylic acid
FT-ICR	Fourier transform ion cyclotron resonance
FTOH	fluorotelomer alcohol
FTSA or FTS	fluorotelomer sulfonate, fluorotelomer sulfonic acid
FtTAoS	fluorotelomer thioether amido sulfonate
FTUCA	fluorotelomer unsaturated carboxylic acid
FWQC	federal water quality goal
GAC	granular activated carbon
GC	gas chromatography
GC/MS	Gas chromatography/mass spectrometry

GEF	Global Environment Facility
GenX	trade name for a polymerization processing aid formulation that contains ammonium 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propanoate
GLI	Great Lakes Initiative
GM	geometric mean
GMAV	genus mean acute value
HA	health advisory
HASP	Health and Safety Plan
HDPE	high-density polyethylene
HFPO-DA	hexafluoropropylene oxide dimer acid
HHRA	human health risk assessment
HI	hazard index
HQ	hazard quotient
HRMS	high-resolution mass spectrometry
HRSC	High-resolution site characterization
IARC	International Agency for Research on Cancer
ICAO	International Civil Aviation Organization
ICV	initial calibration verification
IDA	isotope dilution analysis
IDW	investigation-derived waste
IPEN	International Pollutants Elimination Network
IRIS	Integrated Risk Information System
ITRC	Interstate Technology and Regulatory Council
IX	ion exchange
K_d	bulk partitioning coefficient
K_{oc}	organic carbon partitioning coeffcient
K_{ow}	water/octanol coefficient
LC	liquid chromatography
LC/MS/MS	liquid chromatography/mass spectrometry/mass spectrometry
LCS	lab control sample
LCPFAC	long-chain perfluoroalkyl carboxylate
LDPE	low-density polyethylene
LEAF	Leaching Environmental Assessment Framework
LHA	lifetime health advisory
LHWA	Little Hocking Water Association
LNAPL	light nonaqueous phase liquid
LOAEL	lowest observed adverse effect level
LOEC	lowest observed effect concentration
LOQ	limit of quantitation
MA DEP	Massachusetts Department of Environmental Protection
MAC-QS	maximum acceptable quality standards
MALDI-TOF	matrix-assisted laser desorption/ionization time-of-flight
MCL	Maximum Contaminant Level
MDH	Minnesota Department of Health
MeFASA	*N*-methyl perfluoroalkane sulfonamide
MeFASE	*N*-methyl perfluoroalkane sulfonamido ethanol (var: *N*-methyl perfluoroalkane sulfonamide ethanol)

MeFASAA	*N*-methyl perfluoroalkane sulfonamido acetic acid (var: *N*-methyl perfluoroalkane sulfonamide acetic acid)
MeFOSA	*N*-methyl perfluorooctane sulfonamide
MEP	Multiple Extraction Procedure
ML	method limit
MNA	monitored natural attenuation
MOA	mode of action
MPCA	Minnesota Pollution Control Agency
MRL	minimal risk level, or minimum reporting limit (laboratory analytical)
MRM	multiple reaction monitoring
MS	mass spectrometry
MSD	matrix spike duplicate
MSW	municipal solid waste
MWCO	molecular weight cut-off
NAM	new assessment method
NaPFO	sodium perfluorooctanoate
NAPL	nonaqueous phase liquid
NCOD	National Contaminant Occurrence Database
NER	non-extractable residues
NESHAP	National Emissions Standards for Hazardous Air Pollutants
N-EtFOSA	N-ethyl perfluorooctane sulfonamide
NF	nanofiltration
NFPA	National Fire Protection Association
NGWA	National Groundwater Association
NHANES	National Health and Nutrition Examination Survey
NHDES	New Hampshire Department of Environmental Services
NJ DEP	New Jersey Department of Environmental Protection
NJDWQI	New Jersey Drinking Water Quality Institute
NMeFOSAA	N-Methylperfluorooctane sulfonamidoacetic acid
NOAEL	no observed adverse effect level
NOEC	no observed effect concentration
NOM	natural organic matter
NOx	nitrogen oxides
NPCA	Norwegian Pollution Control Agency
NPDES	National Pollutant Discharge Elimination System
NPDWRs	National Primary Drinking Water Regulations
NPL	National Priorities List
NSF	National Sanitation Foundation
NTP	National Toxicology Program
NWQC	national water quality criteria
NYDEC	New York State Department of Environmental Conservation
O&M	operation and maintenance
OAT	organic anion transporter protein
OC	organic carbon
OCPSF	organic chemicals, plastics and synthetic fibers
OECD	Organisation for Economic Co-operation and Development
OEHHA	Office of Environmental Health Hazard Assessment (California)
OH	hydroxide ion, or hydroxyl group (Helmenstine 2018)

OPEX	operating expenses
ORD	Office of Research and Development (USEPA)
OSB	oriented strand board
OU	operable unit
PAB	permeable absorptive barrier
PA DEP	Pennsylvania Department of Environmental Protection
PAC	powdered activated carbon
PAF	perfluoroalkanoyl fluorides
PAH	polycyclic aromatic hydrocarbon
PASF	perfluoroalkane sulfonyl fluoride
PBSF	perfluorobutane sulfonyl fluoride
PBT	persistent, bioaccumulative, and toxic
PCA	principal components analysis
PCBs	polychlorinated biphenyls
PCE	perchloroethylene
PE	performance evaluation
PFA	perfluoroalkoxy polymer
PFAA	perfluoroalkyl acid
PFAI	perfluoroalkyl iodides
PFAS	per- and polyfluoroalkyl substances
PFBA	perfluorobutanoate, perfluorobutanoic acid, perfluorobutyrate, perfluorobutyric acid
PFBE	perfluorobutyl ethylene
PFBS	perfluorobutane sulfonate, perfluorobutane sulfonic acid
PFC	perfluorocarbon (C_nF_{2n+1}, for example, perfluorooctane) *Do not use this acronym for any other description including perfluorinated compound or perfluorochemical.*
PFCA	perfluoroalkyl carboxylate, perfluoroalkyl carboxylic acid
PFDA	perfluorodecanoate, perfluorodecanoic acid
PFDoA, or PFDoDA	perfluorododecanoate, perfluorododecanoic acid
PFDoS, or PFDoDS	perfluorododecane sulfonate, perfluorododecane sulfonic acid
PFDS	perfluorodecane sulfonate, perfluorodecane sulfonic acid
PFECA	per- or polyfluoroalkyl ether carboxylic acid
PFEI	perfluoroethyl iodide (aka fluorotelomer iodide)
PFESA	per- or poly- fluoroalkyl ether sulfonic acid
PFHpA	perfluoroheptanoate, perfluoroheptanoic acid
PFHpS	perfluoroheptane sulfonate, perfluoroheptane sulfonic acid
PFHxA	perfluorohexanoate, perfluorohexanoic acid
PFHxS	perfluorohexane sulfonate, perfluorohexane sulfonic acid
PFIB	perfluoroisobutylene
PFMOAA	perfluoro-2-methoxyacetic acid
PFNA	perfluorononanoate, perfluorononanoic acid
PFNS	perfluorononane sulfonate, perfluorononane sulfonic acid
PFOA	perfluorooctanoate, perfluorooctanoic acid, perfluorooctane carboxylate
PFOS	perfluorooctane sulfonate, perfluorooctane sulfonic acid
PFOSA, or FOSA	perfluorooctane sulfonamide
PFPA	perfluorophosphonic acid
PFPE	perfluoropolyether
PFPeA	perfluoropentanoate, perfluoropentanoic acid

PFPeS	perfluoropentane sulfonate, perfluoropentane sulfonic acid
PFPiA	perfluorophosphinic acid
PFSA	perfluoroalkyl sulfonate, perfluoroalkane sulfonic acid
PFSiA	perfluoroalkyl sulfinic acid
PFTeDA, or PFTA	perfluorotetradecanoic acid
PFTeDS, or PFTS	perfluorotetradecane sulfonate, perfluorotetradecane sulfonic acid
PFTrDA, or PFTriA	perfluorotridecanoic acid
PFTrDS, or PFTriS	perfluorotridecane sulfonate, perfluorotridecane sulfonic acid
PFUnA, or PFUnDA	perfluoroundecanoate, perfluoroundecanoic acid
PFUnS, or PFUnDS	perfluoroundecane sulfonate, perfluoroundecane sulfonic acid
pg/m^3	picogram per cubic meter
pH	negative log of hydrogen ion concentration (measure of acidity)
PHxSF	perfluorohexane sulfonyl fluoride
PICs	products of incomplete combustion
PIGE	partice-induced gamma-ray emission spectroscopy
PIH	pregnancy-induced hypertension
PILI	polymer with ionic liquid coated iron
PNEC	predicted no-effect concentration
POD	porewater observation device
POE	point of exposure
POET	point of entry treatment
polyDADMAC	Polydiallyldimethylammonium chloride
POP	persistent organic pollutant
POPRC-14	14th meeting of the POPs Review Committee
POSF	perfluorooctane sulfonyl fluoride
POU	point of use
PPAR-α	peroxisome proliferator-activated receptor-α
ppb	parts per billion
PPE	personal protective equipment
ppm	parts per million
ppt	parts per trillion
PPRTV	Provisional Peer-Reviewed Toxicity Values
PSA	prostate-specific antigen
PSD	passive sampling device
PTFE	polytetrafluoroethylene
PUF	polyurethane foam
PVDF	polyvinylidene fluoride
PWS	public water system
QA	quality assurance
QAPP	quality assurance project plan
QC	quality control
QL	quantitation limit
QPD	qualified products database
QPL	Qualified Product Listing
QSAR	quantitative structure-activity relationship
QSM	Quality Systems Manual
qTOF/MS	quadrupole time of flight-mass spectrometry
RAO	remedial action objective

RCRA	Resource Conservation and Recovery Act
REACH	European Chemicals Regulation
RfD	reference dose
RI/FS	Remedial Investigation/Feasibility Study
RIVM	Netherlands National Institue for Public Health and the Environment
RL	reporting limit
RML	removal management level
RO	reverse osmosis
RPD	relative percent difference
RPF	relative potency factor
RSC	relative source contribution
RSL	regional screening level (Note: In many commercial venues RSL means “restricted substances list.”)
RSSCT	rapid small-scale column testing
SAP	Sampling and Analysis Plan
SCWO	supercritical water oxidation
s.d. or SD	standard deviation
SDS	Safety Data Sheet
SDWA	Safe Drinking Water Act
SERDP	Strategic Environmental Research and Development Program
SIP	sorbent-impregnated polyurethane foam
SL	screening level
SMART	specific, measurable, attainable, relevant, and timely (goal)
SMAV	species mean acute value
SML	surface micro layer
SMZ	surface-modified zeolites
SNUR	Significant New Use Rule
SPE	solid-phase extraction
SPLP	Synthetic Precipitation Leaching Procedure
SSD	species sensitivity distribution
STAR	Spill Tactics for Alaska Responders
TANA	Technical Assistance Needs Assessments
TARC	top-layer antireflective coatings
TBC	to-be-considered values
TBEL	technology-based effluent limits
TCE	trichloroethene
TCEQ	Texas Commission for Environmental Quality
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids
TEQ	toxic equivalency quotient
TFE	tetrafluoroethylene
TMDL	total maximum daily loads
TMF	trophic magnification factor
TO	Toxic Organic (method)
TOC	total organic carbon
TOF	time-of-flight
TOP	total oxidizable precursor
TRRP	Texas Risk Reduction Program

TRV	toxicity reference value
TSH	Thyroid-stimulating hormones
TSCA	Toxic Substances Control Act
TTDs	target organ toxicity doses
UCMR	Unregulated Contaminant Monitoring Rule
UF	ultrafiltration
mg/kg	micrograms per kilogram
UL	Underwriters Laboratories
U.S.C.	United States Code
USDOD	United States Department of Defense
USDW	Underground sources of drinking water
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VDEC	Vermont Department of Environmental Conservation
VDH	Vermont Department of Health
VOC	volatile organic compound
WQBEL	water quality-based effluent limits
WV	wildlife value
ww	wet weight
WWTP	wastewater treatment plant
ZVI	zero-valent iron

Updated September 2023.

Glossary

A

Adsorption
The mechanism whereby ions or compounds within a liquid or gas adhere to a solid surface upon contact. The term also refers to a method of treating wastes in which activated carbon is used to remove organic compounds from wastewater.

Anion
A negatively charged ion.

Arithmetic mean
The sum of a collection of numbers divided by the number of numbers in the collection, commonly referred to as the "average".

B

Biochar
A carbon-rich, porous solid synthesized by heating biomass, such as wood or manure, in a low-oxygen environment (pyrolysis).

Biomaterials
Materials derived from plants or animals created for use as sorption materials.

C

Cation
A positively charged ion.

Coagulation
The process of destabilizing a colloid or suspension that unbalances the forces that separate the particles, often by neutralizing the charges on the particles and allowing the particles to clump or settle.

E

Electro precipitation/electrocoagulation
The use of an electrical current to enhance the coagulation and precipitation of ionic compounds. The electrical current may attract the compounds to an anode or cathode, or create coagulating ions from a sacrificial anode, or both.

Empty Bed Contact Time (EBCT)
A measure of the time during which water to be treated is in contact with the treatment medium in a contact vessel, assuming that all liquid passes through the vessel at the same velocity. EBCT is equal to the volume of the empty bed divided by the flow rate (Sacramento State University 2019).

F

Flocculation
A process in which the suspended particles of a destabilized colloid or suspension form groups or clumps (known as a "floc"). Coagulation and flocculation work together to separate solids and liquids containing colloids and suspensions.

Fluorotelomer substance
A polyfluoroalkyl substance produced by the telomerization process.

G

Geometric mean

The central tendency or typical value of a set of numbers, derived by multiplying the numbers in a set then finding the nth root of the product, where "n" is the number of values in the set.

H

Head
The part of a molecule that is a charged functional group attached at one end of the carbon chain tail.

I

Incineration
Thermal destruction process typically characterized by oxidation at temperatures in excess of 1,000°C.

Isomers
Chemicals with the same chemical formula, but different molecular structures.

M

Membrane fouling
Loss of production capacity of a membrane due to accumulation of compounds or biogrowth on the membrane.

Micelles
Particles in which long hydrocarbon tails, repelled by the water molecules and attracted to each other, make up the interior, whereas the negatively charged heads coat the surface and interact with the surrounding water molecules and positive ions (Ege 1999).

Mineralization/decomposition/destruction
The breakdown of a chemical compound into its constituent elements and carbon dioxide and water.

Moiety
A specific group of atoms within a molecule that is responsible for characteristic chemical reactions of that molecule (Helmenstine 2019).

O

Organoclays
A naturally occurring clay mineral that is organically modified to incorporate cations and enhance the sorption capability.

P

Perfluorinated chemical
Subset of PFAS. Have carbon chain atoms that are totally fluorinated. Examples are perfluorooctanoate (PFOA) and perfluorooctane sulfonate (PFOS) (Buck et al. 2011).

Perfluoroalkyl substance
Fully fluorinated alkane (carbon chain) molecule. They have a chain (tail) of two or more carbons atoms with a charged functional group (head) attached at one end.

Permeate
The water treated by a membrane filtration technology, which has passed through the membrane, and from which PFAS have been removed. The contaminants not passing the membrane accumulate in the filtrate, which also does not pass through the membrane.

Polyfluorinated chemical
Subset of PFAS. Have at least one carbon chain atom that is not totally fluorinated (Buck et al. 2011).

Polyfluoroalkyl substance
The molecule has a nonfluorine atom (typically hydrogen or oxygen) attached to at least one, but not all, carbon atoms, while at least two or more of the remaining carbon atoms in the carbon chain tail are fully fluorinated.

Polymer

Large molecules formed by combining many identical smaller molecules.

R

Reactivation
The process of treating regenerated GAC to restore treatment properties.

Redox
Chemical reduction-oxidation processes and conditions that can result in the alteration of a chemical compound.

Regeneration
The act of restoring some of the sorption capacity of a sorptive media (that is, activated carbon or ion exchange) by removing the adsorbed matter. For carbon, regeneration is a thermal oxidation process.

S

Sorption
Removal of a compound from solution by solid phase constituents. This term is often used when the mechanism of removal (adsorption, absorption, or precipitation) is unknown. (Thompson and Goyne 2012).

Stabilization
A process to reduce mobility of compounds in the environment through physical or chemical means.

Surfactant
A surface-active agent that lowers the surface tension of a liquid.

T

Tail
The part of a molecule that is a chain of two or more carbon atoms.

Thermal desorption
Thermal treatment process intended to remove the contaminants from a solid medium (such as soil, sediment, carbon) and drive them into the vapor phase.

Z

Zwitterion
An ionic compound containing both positively and negatively charged groups with a net charge of zero.

Updated September 2023.

Acknowledgments

The members of the Interstate Technology & Regulatory Council (ITRC) PFAS Team wish to acknowledge and thank the individuals, organizations, and agencies that contributed to this online document that includes the PFAS Technical and Regulatory Guidance Document, PFAS Fact Sheets and Explainer Videos, Training Module Videos and external tables of data and information prepared by the ITRC PFAS Team.

The PFAS Team was led by: Bob Mueller, New Jersey Department of Environmental Protection (2017 – 2021); Ginny Yingling, Minnesota Department of Health (2017 – 2020); Kate Emma Schlosser, New Hampshire Department of Environmental Services (2020 – 2022); Sandra Goodrow, New Jersey Department of Environmental Protection (2020 – present); and Kristi Herzer, Vermont Department of Environmental Conservation (2022 – present).

The team leaders were assisted by Program Advisors: Lesley Hay Wilson and Jim Rocco of Sage Risk Solutions LLC. In addition, Josh Criss of GDIT provided video support for the training video modules. Tadbir Singh, ITRC/ECOS Project Associate; Evan Madden, ITRC Project Manager; and Marguerite Bennett, ITRC Project Associate provided support to the team.

During the development and updating of the fact sheets, technical and regulatory guidance document, external tables and training videos the team received many comments and reviews from experts across U.S. EPA, U.S. DOD, U.S. DOE, state agencies, academic institutions, industry, and consulting. This input was invaluable to the development of these ITRC products. The team greatly appreciates those who offered advice, suggestions, reviews and comments.

Specifically, the team wishes to thank and recognize the efforts and important contributions of the team members.

State and Local Government

John Abernathy
South Carolina Department of Health and Environmental Control

Daniel Arthur
Alabama Department of Environmental Management

Heather Barbare
Colorado Springs Utilities

Sara Benovic
Arizona Department of Environmental Quality

Jeff Biggs
City of Tucson Water Department

Rachel Blomberg
Colorado Department of Public Health and Environment

Robyne Bridgman
Virginia Dept. of Environmental Quality

Christine P. Brown
California Department of Toxic Substances Control

Vivek Mathrani
California Department of Toxic Substances Control

Lawrence Matson
Delaware Natural Resources and Environmental Control

Justin Meredith
Tennessee Department of Environment and Conservation- Division of Remediation

Sandra Mort
North Carolina Department of Environmental Quality

Matt Narter
Arizona Department of Environmental Quality

Steve Nelson
City of Austin, Texas

Cherrie Nelson
Wyoming Department of Environmental Quality

Mary Helen Niemann
Texas RR Commission

Robert Burgess
Alaska Department of Environmental Conservation

Sandeep Burman
Minnesota Pollution Control Agency

Bonnie Buthker
Ohio USEPA/ASTSWMO

Sandra Caldwell
Washington Department of Ecology

Jill Clark
Georgia Environmental Protection Division

Jessika Cohen
Oregon Department of Environmental Quality

Hoa Dao
Pennsylvania Department of Environmental Protection

Robert Delaney
Michigan Department of Environmental Quality

Amy Doherty
New Hampshire Department of Environmental Services

Mark Elliott
Minnesota Pollution Control Agency

Chris Evans
Maine Department of Environmental Protection

Cheryl Fields
Connecticut Department of Public Health

Kimberly Gettmann
California USEPA/Department of Toxic Substances Control

Paul Giannoukos
Delaware Natural Resources and Environmental Control

Helen Goeden
Minnesota Department of Health

Sandra Goodrow
New Jersey Department of Environmental Protection

Stephanie Gordon
Delaware Natural Resources and Environmental Control

Rick Greiner
New Mexico Environment Department

Kristi Herzer
Vermont Department of Environmental Conservation

Rebecca Higgins
Minnesota Pollution Control Agency

Fabio Iwashita
New York Department of Environmental Conservation

Marjorie Norman
City of San Antonio

Christine Osborne
Utah Department of Environmental Quality

Sara Pearson
Michigan Department of Environmental Quality

Michael Penzone
Delaware Natural Resources and Environmental Control

Jonathan Petali
New Hampshire Department of Environmental Services

Kerry Pflugh
New Jersey Conference of Mayors

Mallory Pinkowski
Delaware Natural Resources and Environmental Control

Shannon Pociu
Connecticut Department of Energy & Environmental Protection

Gloria Post
New Jersey Department of Environmental Protection

Ron Poustchi
New Jersey Department of Environmental Protection

Angela Preimesberger
Minnesota Pollution Control Agency

Matthew Revel
Alabama Department of Environmental Management

Charles Reyes
ITRC/ECOS

Kristy Richardson
Colorado Department of Public Health and Environment

Louise Roy
Maine Department of Environmental Protection

Patrik Sartz
Alaska Dept of Environmental Conservation

Paul Schleusener
Michigan Department of Environment, Great Lakes, and Energy

Kate Emma Schlosser
New Hampshire Department of Environmental Services

Chuck Schwer
Vermont Department of Environmental Conservation

Shukla Roy-Semmen
California Department of Toxic Substances Control

Samuel Iwenofu
Washington State Department of Ecology

Ricardo Jaimes
DOEE Government of the District of Columbia

Walsta Jean-Baptiste
Florida Department of Environmental Protection

Yujie Jin
California Department of Toxic Substances Engineering

Jason Johnson
New York Department of Environmental Conservation

Mimi (Melanie) Johnson
Wisconsin Department of Natural Resources

Michael Jury
Michigan Department of Environment, Great Lakes, and Energy

Julie Kadrie
Minnesota Department of Health

Sesha Kallakuri
Michigan Department of Health and Human Services

Brandon Kernen
New Hampshire Department of Environmental Services

Annalisa Kihara
California State Water Resources Control Board

Anne Knapp
Washington State Department of Ecology

Lisa Kowalczyk
Arizona Department of Environmental Quality

Gary Krueger
Minnesota Pollution Control Agency

Meghan Lally
Connecticut Department of Energy and Environmental Protection

Gladys Liehr
Florida Department of Health

Gail Lipfert
Maine Department of Environmental Protection

Tim Lockrem
Minnesota Pollution Control Agency

Kevin Lund
Michigan Department of Environmental Quality

Ron MacGillivray
Delaware River Basin Commission

Michael Sexton
Virginia Department of Environmental Quality

Monica Sheets
Colorado Department of Public Health and Environment

Kathryn Shepard Morris
Montana Department of Environmental Quality

Clifford Shierk
Minnesota Pollution Control Agency

Cheryl Sinclair
Pennsylvania Department of Environmental Protection

Tadbir Singh
ITRC/ECOS

Leah Smith
Florida Department of Environmental Protection

Matt Smith
Orange County Sanitation District

Sandra Snyder
South Caroline Department of Health and Environmental Control

Richard Spiese
Vermont Waste Management Division

Brie Sterling
Pennsylvania Department of Environmental Protection

Kara Steward
Washington State Department of Ecology

Christina Stringer
New England Interstate Water Pollution Control Commission

Brock Tabor
Alaska Department of Environmental Conservation

Joy Taylor Morgan
Michigan Department of Environment, Great Lakes, and Energy

Tom Trainor
Wisconsin Department of Natural Resources

Lanita Walker
City of Tallahassee

Thomas Wallace
Mississippi Department of Environmental Quality

Jamie Wallerstedt
Minnesota Pollution Control Agency

Li Wang

Evan Madden
ITRC/ECOS

Kerri Malinowski
Maine Department of Environmental Protection

Craig Manahan
Washington State Department of Ecology

California Department of Toxic Substances Control

Jeff Wenzel
Missouri Department of Health and Senior Services

Tracie White
Colorado Department of Public Health & Environment

Ken Zarker
Washington State Department of Ecology Pollution Prevention & Regulatory Assistance Section

Federal Government

Hunter Anderson
US DOD AFCEC

Jennifer Apell
US Army Corps of Engineers

Timothy Appleman
US DOD NAVFAC EXW

David Asiello
US DOD Office of the Assistant Secretary of Defense (Sustainment)

Caroline Baier-Anderson
USEPA/OLEM/FFRRO

Paul Beam
US DOE HQ EM 4.12, Groundwater and Soil Remediation

Sandip Chattopadhyay
USEPA/ORD

Mary Cooke
USEPA/FFRRO

Jed Costanza
USEPA OSTRI/TIFSD

Anthony Danko
US DOD NAVFAC EXWC

Ramona Darlington Iery
US DOD NAVFAC EXWC

Jeffrey Dvorak
US Army Corps of Engineers

Emily Fabricatore
US DOE Environmental Management

Linda Fiedler
USEPA OSRTI

Melissa Forrest

David Liu
NASA

Cornell Long
US Air Force

Michelle Lordemann
US Army Corps of Engineers

Yvette Lowney
SERDP-ESTCP

Virginia Makale
US DOD Naval Facilities Engineering Command, Southwest

Andy Martin
US Army Engineer Research and Development Center

Lisa Matthews
USEPA Office of Research and Development

Anita Meyer
US Army Corps of Engineers

Beth Moore
US DOE EM-4.31, Office of Regulatory Compliance

Deborah Morefield
US DOD Office of the Deputy Assistant Secretary of Defense (Environment)

Gary Newhart
USEPA-ERT

T. Nicole Nieves
US Army Corps of Engineers

Bonnie Packer
US DOD ARNG

Cara Patton
SERDP-ESTCP

US DOD NMCPHC

Elisabeth Freed
USEPA

Christopher Griggs
US Army Engineer Research and Development Center

Pamela Hamlett
US Air Force

Paul Hatzinger
SERDP-ESTCP

Levi Haupert
USEPA

Hannah Holsinger
USEPA

Thomas Imbrigiotta
USGS (retired)

Christopher Impellitteri
USEPA ORD

David Katz
USEPA Atlantic Ecology Division

Patsy Kerr
US DOD NMCPHC

John Kornuc
US DOD NAVFAC EXWC

Andrea Lehn
US DOD SAF/IE

Kendra Leibman
US DOD Navy

Ron Pinkoski
US Coast Guard

Jessica Reiner
NIST

Ann Richard
USEPA

Amy Rosenstein
US Army Corps of Engineers

Mark Rothas
US Army Corps of Engineers

Andrea Sansom
US Army Corps of Engineers

James Smith
US DOD NMCPHC

Sharon Stone
US DOD AFCEC/CZO

Hans Stroo
SERDP-ESTCP (retired)

James Tarr
US DOD NAVFAC

Wendy Thomi
USEPA Office of Land and Emergency Management

Hilary Thornton
USEPA R4 Superfund

Janice Willey
US DOD NAVSEA

Christopher Zevitas
US Department of Transportation

Emeritus, Public and Tribal Stakeholders

Richard Aho
retired

Doris Cellarius
Sierra Club

Edward (Ted) Emmett
University of Pennsylvania

David Hofmann
Cherokee Nation

Jeffrey Kuhn
Kuhn Environmental

Alexander MacDonald
SanMan Designs

Peter Strauss
PM Strauss & Associates

Eric Uram
Sierra Club

Academia

David Bond
Bennington College

Daniela Castañeda
University of Colorado at Boulder

Michelle Crimi
Clarkson University

Chadi El Mohtar
The University of Texas at Austin

Jennifer Field
Oregon State University

Jennifer Guelfo
Texas Tech University

Megan Hart
University of Missouri Kansas City

Christopher Higgins
Colorado School of Mines

Eric Nuttall
University of New Mexico

Christopher Olivares
University of California – Irvine

Matt Reeves
Western Michigan Univ.

Timothy Schroeder
Bennington College

Mark Widdowson
Virginia Tech

Paul Yaroschak
Water & Environmental Technology Center, Temple University

Industry Affiliates

Stewart Abrams
Langan Engineering & Environmental Services

David Adamson
GSI Environmental Inc.

Jennifer Adler
Haley & Aldrich

Hannah Albertus-Benham
WSP

Ryan Andersen
LANGAN

Janet Anderson
GSI Environmental Inc.

Richard Anthony
Weston Solutions

Lydia Auner
TRC

Matthew Barvenik
GZA GeoEnvironmental, Inc.

Saamih Bashir
WSP

Buddy Bealer
Shell

Stephen Korzeniowski
BeachEdge Consulting

Ronald Kotun
Tetra Tech

Matt Kraus
Tetra Tech

Yasemin Kunukcu
Roux Associates

Matthew Lahvis
Shell

Johnsie Lang
Arcadis

Heather Lanza
CDM Smith

Laurie LaPat-Polasko
Ramboll Environ

Sarah LaRoe
Anchor QEA, LLC

Steven LaRosa
Weston & Sampson

Maureen Leahy
WSP

Melissa Beauchemin
Kennedy/Jenks Consultants

Mark Benotti
NewFields

John Berry
ECT2

Amanda Bess
Chevron

Jeremy Birnstingl
Regenesis

Birgitta Beuthe
BP

Michael Bock
The Intelligence Group, LLC

Dorin Bogdan
AECOM

Francis Boodoo
Purolite

Andrew Borden
AECOM

Jenalle Brewer
Calgon Carbon Corporation

Steven Brown
The Dow Chemical Company

Cristin Bruce
Shell

Dan Bryant
Woodard & Curran

Bob Buck
Chemours

Karla Buechler
Enthalpy Analytical Laboratory

Scott Burkey
Shell

David Burns
OPEC Systems

Stuart Cagen
Shell

Barbara Campany
GHD

Paul Caprio
EA Engineering

Nigel Lewis
HSW Engineering, Inc.

Shangtao Liang
AECOM

Jerry Lisiecki
Clean Harbors Environmental Services

Anne Lockard
Heritage Environmental Services

Linda Logan
Terraphase Engineering, Inc.

Kevin Long
Terraphase Engineering, Inc.

Heather Lutz
Geosyntec Consultants

Tamzen Macbeth
CDM Smith

Matt Machusick
Leidos

Sriram Madabhushi
BAH

Brian Mader
3M Company

Andrew Madison
WSP

Maria Magilton
EA Engineering, Science and Technology

Martha Maier
Montrose Environmental Group

Stefano Marconetto
WSP

Frank Marine
Texas Molecular

Robert Martin
Clean Earth

Matt Matteson
WSP

Chris McCarthy
Jacobs

Katrina McCullough
GHD

Lisa McIntosh
Woodard & Curran

Grant Carey
Porewater Solutions

David Carlson
Enterprise Environmental Advisors

Corey Carpenter
EKI Environment & Water, Inc.

Gwendoline Caviness
Exponent

Bharat Chandramouli
SGS North America

Dora Chiang
WSP

Sabina Chowdhury
BAH

Steve Clough
Haley & Aldrich (retired)

John Collins
AquaBlok

Jason Conder
Geosyntec Consultants

Pete Conwell
Shell

Eliot Cooper
Cascade

Jeff Cornell
Tehama LLC

Thomas Cortina
Cortina Environmental Consulting

Rick Cramer
Burns & McDonnell Engineering Company, Inc.

Kavitha Dasu
Battelle

Rula Deeb
Geosyntec Consultants

Todd DeJournett
Geosyntec

Elizabeth Denly
TRC

Nicholas DeRose
Langan Engineering & Environmental Services

Richard Desrosiers
GZA GeoEnvironmental, Inc.

Angus McGrath
Stantec

Patricia McIsaac
Eurofins

Jason McNew
EA Engineering, Science & Technology

Daniel Medina
AECOM

Dogus Meric
Geosyntec Consultants

Michael Mobile
GZA GeoEnvironmental, Inc.

Mahsa Modiri
EA Engineering, Science, & Technology

Joe Montello
Republic Services, Inc.

Rebecca Mora
AECOM

Austin Morgan
BEM Systems, Inc.

Teri Myers
CDM Smith

Jonathan Naile
Shell

Peter Nangeroni
Woodard & Curran

Charles Neslund
Eurofins

Hilary Nevis
Amec Foster Wheeler

John Newsted
OBG Company

Eric Nichols
Substrata LLC

Mark Nielsen
Ramboll

Ashley Nifong
GEL Labs

Mitchell Olson
Trihydro Corporation

Jeff Orient
Tetra Tech

Erica DiFilippo
S.S. Papadopulos & Associates, Inc.

William DiGuiseppi
Jacobs

Dina Drennan
BEM Systems, Inc.

Thomas Dunder
TRC

Scott Dwyer
Kleinfelder

Richard Evans
GES, Inc

David Favero
RACER Properties LLC

Jim Feild
WSP

Tony Finding
BSTI

Stephanie Fiorenza
Arcadis

Eric Forrester
Calgon Carbon Corporation

Cheryl Fountain
Tetra Tech

Jamie Fox
Enthalpy Analytical Laboratory

Justin Gal
Amec Foster Wheeler

Stephen Geiger
ERM

Bob Gensemer
GEI Consultants, Inc.

David Glaser
Anchor QEA, LLC

Arianne Godwin
Pinyon Environmental, Inc

Jessica Goin
Anchor QEA, LLC

Marat Goldenberg
Burns & McDonnell Engineering Company, Inc.

Sean Gormley
WSP

Fernanda Paes Wilson
Fishbeck

Kanan Patel-Coleman
Burns & McDonnell Engineering Company, Inc.

Michael Penzo
Penzo Consulting

Stephen Pepper
Montrose Environmental Group

Ioana Petrisor
EnSafe

Jenny Phillips
TRC

Jeffrey Pintenich
Brown and Caldwell

Les Porterfield
TEA, Inc.

John Powell
HydroGeoLogic, Inc.

Fred Price
APMI

Emily Pulcher
Burns and McDonnell

Bob Pullano
GEL Laboratories

Joseph Quinnan
Arcadis

LeeAnn Racz
ToxStrategies

Francis Ramacciotti
GHD

Craig Redfern
APTIM

Stephen Rembish
Parsons Corporation

Cynthia Rhode
GHD

William Rish
ToxStrategies, Inc.

Christopher Ritchie
Ramboll

Harrison Roakes
Sanborn, Head & Associates, Inc.

Heather Gosack
WSP

Scott Grieco
Jacobs

Daniel Griffiths
Parsons Corporation

Karen Gruebel
EKI Environment & Water

Chris Gurr
CDM Smith

Adam Hackenberg
Langan Engineering & Environmental Services

Nathan Hagelin
WSP

Jeffrey Hale
Kleinfelder

Linda Hall
DBA Linda C. Hall, PhD

Kris Hallinger
ERM

Ruth Hammervold
Brown and Caldwell

Melissa Harclerode
CDM Smith

Paul Hare
OBG

Ivy Harvey
EA Engineering, Science, Technology, Inc.

Elisabeth Hawley
Geosyntec

Ed Hawthorne
Shell

Ziqi He
HSW Engineering

Jennifer Heath
Heath Toxicology

Nanda Hermes
ERM

Jeffrey Holden
GEI Consultants, Inc.

Rebecca Hollender
TRC

Brian Roh
Burns & McDonnell Engineering Company, Inc.

Nancy Rothman
New Environmental Horizons, Inc.

Aaron Rydecki
WSP

Samantha Saalfield
EA Engineering

Andy Safulko
Brown and Caldwell

John Santacroce
Parsons Corporation

Nicholas Santella
BSTI

Christopher Schaupp
Neptune & Company

Dan Schneider
Terracon

Ron Schoff
Phoenix Pure Holdings LLC

Barrie Selcoe
Jacobs

Joe Seracuse
Brown and Caldwell

Michael Sieczkowski
JRW Bioremediation

David Silbaugh
Silbaugh Hydrogeological Svcs

Cannon Silver
CDM Smith

Lizanne Simmons
Kleinfelder

Brent Smith
Civil & Environmental Consultants

Zachary Smith
Verdantas LLC

Mike Solt
Langan Engineering & Environmental Services

Skyler Sorsby
WSP

Joseph Sposato
Pinyon Environmental, Inc.

Christopher Hook
Tetra Tech, Inc.

Chuck Hornaday
Vadose Remediation Technologies

Peggy Horst
W.L. Gore & Associates, Inc.

Erika Houtz
ect2

Brian Hoye
Burns & McDonnell Engineering Company, Inc.

Jane Huber
Metiri Group

Ryan Hultgren
Kennedy/Jenks

Gary Hunt
TRC

Craig Hutchings
Integral Consulting Inc.

Antone Jain
EKI Environment & Water

Thomas M. Johnson
Thomas Johnson Associates

Daniel Jones
AECOM

Purshotam Juriasingani
Tetra Tech, Inc.

Ellen Kaastrup
Kaastrup Consulting, LLC

Lisa Kammer
Weston Solutions, Inc.

Saroj Kandel
Civil & Environmental Consultants, Inc.

William Kerfoot
Kerfoot Technologies, Inc.

Trent Key
ExxonMobil

Eric Klinker
DuPont

Mat Knutson
Terracon

Stephen Koenigsberg
Montrose Environmental Group

Kendall St. Ange
TRC

Brent Stafford
Shell

Jamie Suski
EA Engineering

Ward Swanson
Barr Engineering Co.

Bob Symons
Eurofins Environment Testing, Australia

Sagar Thakali
AECOM

Ryan Thomas
Parsons Corporation

Shalene Thomas
Battelle Memorial Institute

Roy Thun
GHD

Derek Tomlinson
GEI Consultants, Inc.

Adam Tressler
ERM

Grant Trigger
RACER Properties LLC

Laura Trozzolo
TRC

Edward (Ted) Tyler
Stantec

Brad Varhol
EON Products

Usha Vedagiri
WSP

Chris Voci
Terraphase Engineering, Inc.

Lisa Voyce
HDR

Claudia Walecka-Hutchison
Dow, Inc.

Ying Wang
WSP

Rick Wice
Battelle Memorial Institute

Artie Wickham
BEM Systems, Inc.

Michael Wilken
The Dow Chemical Company

Jason Wilkinson
Ramboll Environ

Anna Willet
LANGAN

Scott Wilson
Regenesis

David Woodward
AMEC Foster Wheeler

Sandra Yi-Fuller
Shell

Rachel Zajac-Fay
Jacobs

Michael Zelenka
ExxonMobil

Stephen Zemba
Sanborn, Head & Associates, Inc.

Lesa Zimnawoda
BEM Systems

Jennifer Zorinsky
AECOM

Barry Zvibleman
Onion Enterprises PFOS-PFOA Treatment

International Team Members

Frank Berger
AECOM

Sarah Gewurtz
Environment and Climate Change Canada

Andrew Mitchell
Department of Defence (Australia)

Niall Ramsden
LASTFIRE

Updated September 2023.

Team Contacts

Team Leaders

Kristi Herzer
Vermont Department of Environmental Conservation
Kristi.Herzer@vermont.gov

Sandra Goodrow
New Jersey Department of Environmental Protection
Sandra.Goodrow@dep.nj.gov

Program Advisors

Lesley Hay Wilson
Sage Risk Solutions LLC
lhay_wilson@sagerisk.com

Jim Rocco
Sage Risk Solutions LLC
jrocco@sagerisk.com

History, Use and Naming Conventions

Jeffrey Wenzel
Missouri Department of Health and Senior Services
Jeff.Wenzel@health.mo.gov

Elizabeth Denly
TRC
edenly@trccompanies.com

Firefighting Foams

Richard Spiese
Vermont Waste Management Division
richard.spiese@vermont.gov

Shalene Thomas
Battelle
Thomass3@battelle.org

Fate and Transport, Site Characterization, Physical and Chemical Properties

Robert Burgess
Alaska Department of Environmental Conservation
robert.burgess@alaska.gov

Ryan Thomas
Parsons
ryan.thomas@parsons.com

Human and Ecological Health Effects, Regulations and Site Risk Assessment

Brie Sterling
Pennsylvania Department of Environmental Protection
bsterling@pa.gov

Linda Hall
Consulting Toxicologist
lindachall@comcast.net

Sampling and Analytical Methods

Janice Willey
U.S. DOD, NAVSEA
janice.l.willey.civ@us.navy.mil

Martha Maier
Montrose Environmental Group
mmaier@montrose-env.com

Treatment Technologies

Cliff Shierk
Minnesota Pollution Control Agency
clifford.shierk@state.mn.us

Andy Safulko
Brown and Caldwell
Asafulko@brwncald.com

Surface Water Quality

Alex MacDonald
SanMan Designs
alexmacd836@gmail.com

Linda Logan
Terraphase Engineering
linda.logan@terraphase.com

Training

Kristi Herzer
Vermont Department of Environmental Conservation
kristi.herzer@vermont.gov

Mitch Olson
Trihydro
MOlson@trihydro.com

Stakeholder Perspectives

Peter Strauss
PM Strauss & Associates
petestrauss1@comcast.net

Updated September 2023

ITRC & Environmental Justice – A Commitment to Our Values

Environmental Justice is making its way to the forefront of today's environmental community following decades of documentation detailing the disproportionate burden placed on low-income and minority communities by pollution and environmental hazards. Failure to address EJ concerns has led to grave consequences for low-income or minority communities; without a voice, human health in these communities can suffer greatly as a result of poorly informed environmental decision-making.

Defined by the United States Environmental Protection Agency (EPA) as "…the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies," EJ can only be achieved when everyone has "the same degree of protection from environmental and health hazards, and equal access to the decision-making process to have a healthy environment in which to live, learn, and work." (USEPA, 2020a). Since its inception in the early 1980s, the field of EJ has grown to encompass a broad spectrum of other environmentally inclusive subjects, concerns and, ultimately, legislation; some of the terminology commonly used today includes Social Equity, Social Impact, and Environmental Equity.

Signed on February 16th, 1994, Executive Order 12898 officially recognized EJ on a federal level, directing agencies to focus attention on the environmental and human health effects of federal actions on minority and low-income populations (USEPA 2020b). Further executive action has been seen recently with the signing of Executive Order 13990, on January 20, 2021, which established White House and Inter-Agency Environmental Justice Councils, as well as the Justice40 Initiative for federal identification and investment in disadvantaged communities (Federal Register, 2021). Another milestone was met when New Jersey became the first state in the nation to adopt legislation on permitting requirements based on EJ. Signed on September 18, 2020, Senate Bill 232 requires the New Jersey Department of Environmental Protection "to evaluate the environmental and public health impacts of certain facilities on overburdened communities when reviewing certain permit applications." (O'Connor, 2020).

ITRC will continue to develop reference material for project managers and environmental professionals to consider in the use of current and future ITRC guidance materials in environmental decision-making and project design. ITRC will include the principals of EJ in future environmental products – working towards our mission while paying express attention to our core values of diversity, equity, inclusion and transparency. ITRC is excited to be a part of addressing environmental justice and bringing more voices to addressing the national and local environmental challenges.

ITRC Organizational Diversity, Equity & Inclusion

Diversity, equity, inclusion and transparency are embodied within the core values of ITRC. They are fulfilled in the pursuit of ITRC's mission and vision. ITRC's Membership Code of Conduct requires every member to benefit from team consensus and collaboration. ITRC requires diverse perspectives that provide the knowledge and skills to address all environmental challenges in pursuit of developing innovative products.

References

Federal Register. Protecting public health and the environment and Restoring science to tackle the climate crisis. (2021, January 25). Retrieved May 07, 2021, from https://www.federalregister.gov/documents/2021/01/25/2021-01765/protecting-public-healthand-the-environment-and-restoring-science-to-tackle-the-climate-crisis

USEPA (a). Environmental Justice. (2020, December 07). Retrieved December 30, 2020, from https://www.epa.gov/environmentaljustice

USEPA (b). Summary of Executive Order 12898 – federal actions to address environmental justice in minority populations and low-income populations. (2020, July 23). Retrieved May 07, 2021, from https://www.epa.gov/laws-regulations/summary-executive-order-12898-federal-actions-address-environmental-justice

O’Connor, C. (2020, October 23). New Jersey’s First in the Nation State Environmental Justice Law. Retrieved January 07, 2021, from https://www.jdsupra.com/legalnews/new-jersey-s-first-in-the-nation-state-10124/

2010/15 PFOA Stewardship Program

Guidance on Reporting Emissions and Product Content

October 2006

Office of Pollution Prevention and Toxics
U.S. Environmental Protection Agency

NMOGA Exhibit D6

Table of Contents

1. Introduction

1.1 Background

On January 25, 2006, Administrator Stephen Johnson invited eight major fluoropolymer and telomer manufacturers to participate in a global stewardship program on perfluorooctanoic acid (PFOA) and related chemicals. Participating companies were asked to commit to reducing PFOA and related chemicals from facility emissions and in product content by 95% no later than 2010, and to work toward eliminating PFOA from emissions and in product content no later than 2015. All eight companies, Arkema, Asahi, Ciba, Clariant, Daikin, DuPont, 3M/Dyneon, and Solvay Solexis, submitted letters of commitment to the PFOA Stewardship Program by the March 1, 2006 deadline.

1.2 Scope of the PFOA Stewardship Program

Each of the eight companies expressed support for a global stewardship program addressing reductions in PFOA, PFOA precursor chemicals, and related higher homologues from both emissions and product content. Participation in the stewardship program is in addition to a company's existing commitments to the Agency. Companies also expressed their general commitment to continue their ongoing research on the sources, pathways of exposure, and potential risks of these chemicals.

1.3 Baseline Data Report

As a means of measuring continuing improvement in achieving reductions, the Stewardship Program specified that individual companies use year 2000 data as the baseline of their company’s emissions and product content. The companies have agreed to submit baseline information by October 31, 2006. If no data are available for year 2000, companies have agreed to use as a baseline the nearest year for which data are available.

1.4 Annual Reports

Companies in the Program have agreed to submit annual reports on their progress toward meeting the goals by the end of October of every year. As noted in Administrator Johnson’s invitation letter, companies would report their progress publicly in terms of company-wide percentage achievements both for U.S. operations and for the company's global business. The Administrator’s letter further noted that companies would also provide to EPA detailed information on their progress in support of their public reports, and would allow EPA to share information submitted under the Program with the Agency’s contractors, including information contained within detailed progress reports that may be claimed as confidential. The first annual progress reports should be submitted by October 31, 2007. However, some companies have expressed their desire to report the reductions already achieved to date, and EPA encourages such submissions to be made in conjunction with the baseline data report submissions.

Some participating companies indicated that the PFOA Stewardship Program could be an umbrella encompassing all of the various pollution prevention, research, and product development activities they are already planning or carrying out in connection with these chemicals. Companies are encouraged to provide such information in their annual reports.

1.5 Data Quality

For all data and information gathered under the PFOA Stewardship Program, the companies committed to employing scientific practices, protocols and procedures designed to ensure data quality, objectivity, utility and integrity. Each annual submission should include a brief discussion of data quality measures employed in composing the final report.

2. Guidance on Reporting Emissions

EPA developed the model-facility reporting form to facilitate a consistent reporting format among companies for the detailed information being submitted in support of each company's summary initial baseline and annual public reports. The form is based on the reporting form from the Use and Exposure Information Project (UEIP) that was developed through a collaborative effort between industry representatives and EPA's Office of Pollution Prevention and Toxics (OPPT). The form was designed specifically to minimize the need for submitters to assert Toxic Substances Control Act (TSCA) Confidential Business Information (CBI) claims, and has been used successfully for more than a decade by some of the companies currently involved in the PFOA Stewardship Program.

The UEIP was a voluntary program, developed initially as a joint effort by the Chemical Manufacturers Association[1] (CMA), the Synthetic Organic Chemical Manufacturers Association (SOCMA), and OPPT, to provide a method for chemical manufacturers to send use and exposure information to OPPT for the chemicals entering the Risk Management screening assessment process. The above groups, as well as the American Petroleum Institute (API) and Chemical Specialty Manufacturers Association (CSMA) developed the original UEIP form in a collaborative effort. The original UEIP form was slightly modified to make it more closely suit the purposes and objectives of the PFOA Stewardship Program. For example, the sections containing exposure-related information were eliminated.

The facility reporting form on emissions is Appendix C of this guidance document. The form is chemical- and site-specific, and requests information on chemical releases at sites where a company manufactures, processes, or uses the chemical. Companies should complete a separate form for each facility. If a company is reporting for more than one chemical, it should complete a separate form for each chemical (PFOA, PFOA precursor chemical, or related higher homologue). Further guidance can be found in the reporting form in Appendix C.

EPA will use information on facility reports on emissions to measure progress toward meeting the goals of the PFOA Stewardship Program. To ensure transparency in reporting, as

---

[1] Now the American Chemistry Council (ACC)

well as in Agency and company decision making, the Stewardship Program is designed to collect information in a format that is readily accessible to the public. Although the submission of CBI under the Stewardship Program is discouraged, EPA recognizes that there may be various circumstances in which a company may need to claim some of its information as TSCA CBI. Appendix B contains information relevant to CBI submissions. A sanitized version of any CBI information should also be submitted, which should disclose as much information as possible. If no claim of confidentiality is made at the time of submission, the detailed information may be made available to the public without further notice by EPA.

3. Guidance on Reporting Product Content

EPA recognizes that there are still many difficulties associated with obtaining accurate and reproducible results in chemical analyses of perfluorinated alkylated compounds. To ensure that the results reported under the Stewardship Program are both comparable and reliable, companies have committed to work with EPA, other PFOA Stewardship Program participants, and other experts in order to establish scientifically credible analytical standards and laboratory methods for measuring the chemicals in the program by 2010, the first goal attainment year.

EPA also recognizes that some of the companies have made significant progress in developing analytical techniques on their own. Companies are encouraged to publicly share these advances with others.

The facility reporting form on product content is Appendix D of this guidance document. This form was developed to provide a consistent reporting format across companies for the detailed information being submitted in support of each company's initial baseline and annual summary public report The form is product- and site-specific. Companies should complete a separate form for each facility. If a company is reporting for more than one product, it should complete a separate form for each product. Further guidance can be found in the reporting form in Appendix D.

EPA will use information on facility reports on product content to measure progress toward meeting the goals of the PFOA Stewardship Program. To ensure transparency in reporting, as well as in Agency and company decision making, the Stewardship Program is designed to collect information in a format that is readily accessible to the public. Although the submission of CBI under the Stewardship Program is discouraged, EPA recognizes that there may be various circumstances in which a company may need to claim some of its information as TSCA CBI. A sanitized version of any CBI information should also be submitted, which should disclose as much information as possible. If no claim of confidentiality is made at the time of submission, the detailed information may be made available to the public without further notice by EPA.

4. Public Summary Reports

The public summary reporting form for the baseline year information can be found in Appendix E. The public summary annual reporting form for reporting reductions in emissions and product content can be found in Appendix F. These reporting forms were developed to provide a simple, convenient, consistent, and readily understandable format in which to summarize emission and product content reductions across company operations in the U.S. and worldwide. As contemplated by Administrator Johnson's invitation letter, the public summary reports provide a means for companies to express their progress in terms of company-wide percentage achievements both for U.S. operations and for the company's global business.

Once submitted by the companies, these forms will be posted on the PFOA Stewardship Program website for easy public reference. They must not contain any CBI. In those sections of the form that may cover information that your company claims as CBI, please fill in the form with as much non-CBI information as possible using ranges or generic descriptions.

5. Submissions to EPA

5.1 Public Record

All submissions under this Stewardship Program will be made publicly available in Docket EPA-HQ-OPPT-2006-0621 unless confidentiality is claimed at the time the information is submitted. EPA has made an electronic version of the public docket available at http://www.regulations.gov.

To access the electronic dockets through http://www.regulations.gov, from the main page locate the "Advanced Search" tab and select "Docket." On the search screen that appears, enter the appropriate docket ID number in the "Docket ID" field and click "Search." The public can also access the EPA-HQ-OPPT-2006-0621 Docket through the EPA Docket Center Reading Room, which is located in the EPA Headquarters Library, Infoterra Room, EPA West, Rm. 3334, 1301 Constitution Avenue, N. W., Washington, D.C.

5.2 Confidential Business Information (CBI)

Although the submission of CBI under the Stewardship Program is discouraged, EPA recognizes that there may be various circumstances in which a company may need to claim some of its information as TSCA CBI. Information claimed CBI will be treated in accordance with the procedures in 40 CFR part 2 and section 14 of TSCA, 15 U. S. C. 2613. Appendix B provides guidance on the submission of CBI to the Agency.

5.3 Submissions to EPA

All documents submitted to EPA under this Program should be identified by the Docket ID Number EPA-HQ-OPPT-2006-0621.

To ensure timely processing, EPA requests that the companies submit one (1) paper copy (marked as CBI where appropriate) and one (1) electronic copy (on a disk or CD ROM; marked as CBI where appropriate and in text-searchable, PDF format) of all documents submitted under this Program to the OPPT Document Control Office in accordance with the procedures specified below. For any CBI submissions, a second copy of the submission (paper and electronic), from which all the marked information and legends are removed, should accompany the submission leaving only the non-confidential portions of the submission.

Submissions made by hand delivery or courier (EPA's preferred option of receiving document submissions for this Program)
Deliver to: OPPT Document Control Office (DCO) in the EPA East Building, Room 6428, 1201 Constitution Avenue, NW, Washington, DC, and mark Attention: Docket ID Number EPA-HQ-OPPT-2006-0621. The DCO is open from 8:00 a.m. to 4:00 p.m., Monday through Friday, excluding legal holidays. The telephone number for the DCO is (202) 564-8930.

Submissions made by mail
Send to: Document Control Office (7407M), Office of Pollution Prevention and Toxics (OPPT), Environmental Protection Agency, 1200 Pennsylvania Avenue, NW, Washington, DC 20460-0001. Mark Attention: Docket ID Number EPA-HQ-OPPT-2006-0621. No electronic media should be submitted to the EPA by mail because it would be destroyed by current mail screening irradiation procedures.

Submissions made electronically
Send to: OPPT Document Control Office at oppt.ncic@epa.gov, Attention: Docket OPPT-2006-0621. Electronic submissions for all reporting under this Program should be submitted as attachments to the e-mail and should be in text-searchable, PDF format. The e-mail transmitting any report required by this Program and all electronic attachments should be included as part of the submission. E-mail addresses are automatically captured by the EPA e-mail system and become part of the submission that is placed in the official public docket, and will be made available in the EPA electronic public docket. Upon receipt of the electronic submission, a "receipt date" is entered into the metadata to signify the date the document(s) submitted by the company(ies) was received by EPA. EPA is not responsible for any submissions that fail to transmit when the EPA firewall rejects an electronic submission containing a virus or other adverse electronic coding. Submitter should confirm that: 1) electronic submissions are received by EPA on the date of transmission, 2) the electronic submission and all attachments are legible, and 3) the electronic submission and all attachments meet the electronic format requirements of the EPA Document Control Office. Do not submit any report containing confidential business information (CBI) to EPA by e-mail.

For all <u>non-CBI</u> submissions, one (1) additional paper and one (1) electronic (searchable PDF) copy of each document should be transmitted directly by a commercial courier or hand delivery to Mary Dominiak in the EPA East Building, Room 4410M, 1201 Constitution Avenue, NW, Washington, DC and marked Attention: 2010/15 PFOA Stewardship Program.

CBI information that is provided to EPA should be sanitized to protect CBI but provide as much information to the public as possible. Any part of data or other documentation claimed as CBI should be so marked. Confidential portions of any particular page should be clearly marked by highlighting, bracketing, or some other marking that clearly identifies the precise information that is claimed as CBI. In addition to the marked copy, a second copy of the submission should accompany the submission from which all the marked information and legends are removed, leaving only the non-confidential portions of the submission. Data or other information that are claimed as CBI should not be submitted electronically to EPA by e-mail.
If the CBI submission is on diskette or CD ROM, mark the outside of the diskette or CD ROM as CBI and then identify electronically within the diskette or CD ROM the specific information that is CBI.

Appendix A

Glossary of Terms

Glossary of Terms

The following definitions should be considered general and applicable to the 2010/15 PFOA Stewardship Program only.

Byproduct
A chemical substance produced without a separate commercial intent during the manufacture or processing of another chemical substance or mixture.

CBI
Confidential Business Information.

ECA
Enforceable Consent Agreement.

Externally recycled
Recovered at another site and then transferred into the subject site for reuse.

Higher homologue chemicals
PFOA and PFOS are both eight-carbon chain length chemicals. Chemicals similar in structure to PFOA or PFOS but with nine or more carbons in the chain are higher homologues of PFOA or PFOS.

Homologue
One of a series of compounds, each of which has a structure differing regularly by some increment (number of carbons, presence of a CH_2 group) from adjacent members of the group.

Impurity
A chemical substance that is unintentionally present with another chemical substance.

Internally recycled
Recovered and reused at the same site.

NPDES
National Pollution Discharge Elimination System.

PFAC
Perfluoroalkyl carboxylate is a generic term used to describe a fully fluorinated carboxylic acid of any carbon chain length, including PFOA.

PFAS
Perfluoroalkyl sulfonate is a generic term used to describe a fully fluorinated sulfonate of any carbon chain length, including PFOS.

PFNA

Perfluorononanoic acid is a fully fluorinated, nine-carbon chain carboxylic acid (C9) (CAS 375-95-1).

PFOA

Perfluorooctanoic acid is a fully fluorinated, eight-carbon chain carboxylic acid (C8) (CAS 335-67-1).

POTW

Publicly Owned Treatment Works.

Precursor

A chemical that can break down to form another chemical. For example, some residual monomer chemicals from the telomer manufacturing process, such as telomer alcohols and telomer iodides, are PFOA precursors because they may remain in the final product and can break down into PFOA.

Product

For the purpose of this Program, the term "product" refers to basic fluorochemical substances or mixtures that are manufactured by the eight fluoropolymer and telomer companies. For example, the chemical substance polytetrafluoroethylene may be sold as a commercial chemical product in the form of a solid or as a diluted aqueous dispersion. Other fluoropolymers, fluorotelomer-based polymers, and telomer monomers that are in commerce (for example, sold to formulators as constituents for incorporation into other formulated products such as inks, paints, cleaners, and surface treatment applications for carpets, textiles, leather, and paper) would be included in the definition of "product" because they are commercial chemical substances. The final formulations themselves, and the articles to which they may be applied (such as carpet, textiles, and paper), are not included in the definition of "product" for the purpose of reporting under the PFOA Stewardship Program.

RCRA

The Resource Conservation and Recovery Act.

Telomer Based Product

Chemical substances that have the fluoroalkyl portion of the molecule derived from telomers manufactured from low molecular weight polymerization of tetrafluoroethylene.

UEIP

Use and Exposure Information Project.

Appendix B

Guidance on Reporting Confidential Business Information (CBI)

2010/15 PFOA Stewardship Program

Guidance on Reporting Confidential Business Information (CBI)

Under TSCA, a company may claim that information provided to EPA is confidential business information (CBI) entitled to confidential treatment. Please note that EPA may request a company to substantiate any CBI claim. You are advised that if no CBI claim accompanies your submission, EPA may make the information available to the public. If you make a CBI claim in the submission, the information covered by such claims will only be disclosed to the extent and by means of the procedures set forth in 40 CFR 2.201 *et seq.* and at 41 FR 36902, Sept. 1, 1976, as amended by 50 FR 51662, Dec. 8, 1985.

If you submit information claimed as CBI, please follow the procedures set forth in 40 CFR 2.201 *et seq.* and at 41 FR 36902, Sept. 1, 1976, as amended by 50 FR 51662, Dec. 8, 1985. In summary, these regulations provide that a company that submits information to EPA may designate all or part of the information as CBI. The submitter should clearly mark an attached cover sheet and each page that contains CBI with the term "Confidential," "Trade Secret," "Proprietary," or other appropriate term indicating the confidential nature of the information contained on that page. Confidential portions of any particular page should be clearly marked by highlighting, bracketing, or some other marking that clearly identifies the precise information that is claimed as CBI. In addition to the marked copy, a second copy of the submission, from which all the marked information and legends are removed, should accompany the submission leaving only the non-confidential portions of the submission. This second copy will be placed in public files and will not be handled as CBI. The submitter may, if known, indicate the period of time for which the company will consider the information as CBI.

Because non-confidential data may be available to the public, it is very important to determine which information is confidential before completing the form. Submitters of the form should be sensitive to information their customers may hold confidential, and should refer to any confidential disclosure agreement with them. If you are in doubt concerning customer CBI, please consult the customer or the appropriate department in your company.

Any questions about how to assert or make CBI claims should be directed to Scott Sherlock, Office of Pollution Prevention and Toxics, at sherlock.scott@epa.gov or 202-564-8257.

Appendix C

Draft Facility Report on Emissions

2010/15 PFOA Stewardship Program
Draft Facility Report on Emissions

I. CHEMICAL IDENTIFICATION

Identify the chemical for which you are submitting information:

Chemical name:______________________

CAS number:________________________

II. COMPANY IDENTIFICATION

Identify the company and location of the facility submitting information:

Company name:________________________________

Site location:___________________________________

Identify a company technical contact who can respond to inquiries about the information submitted:

Technical contact:_________________________________
Phone:____
Address:____

III. ON-SITE ACTIVITIES

Calendar year for which you are reporting: Jan 1, 20___ to Dec 31, 20 ___

Provide the amount of chemical identified above for the reporting year at specific site:

Imported (virgin)	__________kgs/yr
Imported (externally recycled)	__________kgs/yr
Manufactured	__________kgs/yr

Estimate the amount of subject chemical distributed off-site:

__________% of manufacture/import

Provide the amount used (including any that was manufactured, imported [virgin or externally recycled], or internally recycled) of the subject chemical for the reporting year at specific site:

__________kgs/yr

Narrative Description and Process Flow Schematic:

Provide overall material balance of the chemical being reported, showing releases and products (kgs/year). Use the following page to provide a narrative description and process flow schematic of on-site activities, and include information that gives an understanding of the nature and extent of potential exposures to the subject chemical. Attach additional pages if desired. The narrative and process flow schematic should cover major unit operations and chemical conversions for manufacturing and on-site uses, if applicable. The narrative should provide insight into why and how releases are caused by the process. The schematic should show the points of release of the subject chemical in the workplace and to the environment. In the event the subject chemical is used in many different processes, provide information on each major process instead of each individual process.

Narrative Description and Process Flow Schematic:

IV. SITE RELEASE AND TRANSFER INFORMATION

(For manufacturing and on-site processing/use if applicable)

In this section, estimate the total media-specific releases after on-site treatment of the chemical from your facility. You may estimate the releases by using monitoring data or any other method you believe appropriate. Estimates should be reported in kgs per year for the reporting period. Enter the values as whole numbers to no more than two significant figures. For example, if your annual releases are estimated to be 12,360 kgs, an estimate of 12,000 kgs should be reported.

Estimate the number of days per year the release occurs. Enter a whole number with a maximum of 2 significant figures.

Insert “NA” for release activities not associated with the chemical or “0” for releases of less than 0.5 kgs per year.

For all releases, the source of data and/or basis for determination should be described in detail. Suggested information about the possible sources/basis includes:

1. If the source/basis is an analytical measurement, then
   - Describe the method (including analytical standards used, sampling, sample treatment, analysis).
   - Describe the uncertainties and assumptions made.
   - Give the Level of Detection (LOD)/Level of Quantification (LOQ).

2. If the source/basis is a mass balance, then
   - Show the mass balance calculation.
   - Show that the mass balance closes.
   - If the mass balance does not close, then report the fraction of total feedstock that is not accounted for and the assumptions you made to correct the balance. Describe the uncertainties.

3. If the source/basis is other than measurement or mass balance, then
   - Describe the method used. For example, if engineering calculations are used, give a general description and state your assumptions. Describe the uncertainties.

Part IV (cont.)

A. ON-SITE AIR RELEASES

Estimate the total fugitive or non-point releases to air and the number of days per year the releases occur. These releases include equipment leaks from valves, pump seals, flanges, compressors, sampling connections, and open-ended lines; evaporative losses from surface impoundments and spills; releases from building ventilation systems; and, any other fugitive or non-point air emission.

In addition, estimate the total releases that occur through stacks, vents, pipes, or other confined air streams as stack or point source releases. Include storage tank emissions and releases from pollution control equipment.

If desired, you can provide estimates of the accuracies of your release estimates.

	Estimated Total Annual Releases (kgs)	Estimated % Accuracy (Optional)	# Days/year Release Occurs
Fugitive (non-point)	_____	_____	_____
Stack (point)	_____	_____	_____

Basis for each release estimate:
(See discussion on source/basis in beginning of Section IV.)

Comments:
(This section is available to clarify your responses. Attach additional pages if desired.)

Part IV (cont.)

B. WATER RELEASES FROM SITE

Estimate the total releases of the chemical leaving the fence line of your facility from all discharge points to all streams or water bodies. Include all discharges from process outfalls such as pipes, open trenches, releases from on-site wastewater treatment, and contribution from storm water runoff, if applicable. Do not include discharges to a POTW or other off-site wastewater treatment facilities. If desired, you can provide an estimate of the accuracy of your release estimate.

	Estimated Total Annual Releases (kgs)	Estimated % Accuracy (Optional)	# Days/year Release Occurs
Water releases:	_____	_____	_____

Enter the names of the streams or water bodies to which the facility directly discharges the chemical. Also, enter the NPDES permit number for the facility. If more than one number is assigned to the facility, list each number for the appropriate discharge quantity and receiving water identified.

Receiving Water Name(s):____________

NPDES number(s):_______________

Basis for each release estimate:
(See discussion on source/basis in beginning of Section IV.)

Comments:
(This section is available to clarify your responses. Attach additional pages if desired.)

Part IV (cont.)

C. ON-SITE LAND RELEASES

Estimate the total releases of the chemical for each category of land disposal, if applicable. Estimate only on-site releases. Do not estimate leaks from landfills separately. This should be accounted for in your estimate of total landfill release.

Releases to land treatment/land amendment include all waste containing the chemical that is applied or incorporated into soil on-site. Do not include waste that is landfilled.

Surface impoundments are natural topographic depressions, man-made excavations, or diked areas formed primarily of earthen materials designed to hold an accumulation of the chemical.

Underground injection is the technology of placing fluids underground, in porous formations of rocks, through wells or other similar conveyance systems.

Other releases include any amount of the chemical that is released to land other than those listed. An example is the accidental release of the chemical from an underground pipeline or storage tank.

	Estimated Total Annual Releases (kgs)	Estimated % Accuracy (Optional)
Landfill	_____	_____
Land Treatment/Land Amendment	_____	_____
Surface Impoundments	_____	_____
Underground Injection	_____	_____
Other (specify):	_____	_____

Basis for each release estimate:
(See discussion on source/basis in beginning of Section IV.)

Comments:
(This section is available to clarify your responses. Attach additional pages if desired.)

Part IV (cont.)

D. OFF-SITE TRANSFERS

Estimates of off-site transfers should be similar in accuracy and precision to previous release estimates.

Dl. Transfer to Publicly Owned Treatment Works (POTW)

Number of days/year the release occurs: _____

Estimate the total quantity of the subject chemical, not the waste stream, transferred to the POTW. Complete section below for each POTW to which your facility discharges wastewater containing the chemical. Enter the POTW's NPDES permit number, if known.

Annual Transfer (kgs): _____

Estimated % Accuracy of Transfer Estimate (optional) _____

POTW Name:____________________________
Street Address: ____
City: ________________
County: ______________
State: _____
Zip Code: _____

NPDES number: _______________________

Basis for each release estimate:
(See discussion on source/basis in beginning of Section IV.)

Comments:
(This section is available to clarify your responses. Attach additional pages if desired.)

Part IV (cont.)

D2. Transfers to other off-site locations

In this section, estimate the quantity of the subject chemical, not the waste stream, transferred and the accuracy of the estimate for each category listed. If your facility sends the subject chemical in waste to an off-site location where some of the chemical will be recycled and the remainder will be treated, estimate each amount separately (i.e., waste treatment and recycling activities).

	Estimated Annual Transfers (kgs)	Estimated % accuracy (Optional)
Incineration	_____	_____
Wastewater Treatment (Excluding POTW)	_____	_____
Underground Injection	_____	_____
Hazardous Waste (RCRA Subtitle C) Landfill	_____	_____
Other Landfill	_____	_____
Recycle or Recovery (Does not include internally recycled)	_____	_____
Internally Recycled	_____	_____
Unknown or Other	_____	_____

Basis for each release estimate:
(See discussion on source/basis in beginning of Section IV.)

Comments:
(This section is available to clarify your responses. Attach additional pages if desired.)

Appendix D

Draft Facility Report on Product Content

2010/15 PFOA Stewardship Program

Draft Facility Report on Product Content

I. CHEMICAL IDENTIFICATION

Identify the product (e.g fluoropolymer dispersion) for which you are submitting information:

Product name:____

Product description (including concentrations of perfluoroalkyl chemicals identified in Section IV below and year of production):
____
____

II. COMPANY IDENTIFICATION

Identify the company and location of the facility submitting information:

Company name:________________________________

Site location:___________________________________

Identify a company technical contact who can respond to inquiries about the information submitted:

Technical contact:__________________________________
Phone:____
Address:____

III. PRODUCTION

Calendar year for which you are reporting: Jan 1, 20___ to Dec 31, 20 ___

Provide the amount of the product for the reporting year at each specific site:

Imported __________kgs/yr

Manufactured __________kgs/yr

IV. PRODUCT CONTENT

A. CONCENTRATIONS OF RELEVANT PERFLUOROALKYL CHEMICALS

Please provide the concentrations (ppb) of various perfluoroalkyl chemicals in your product. For chemicals for which you do not have actual data, please provide range estimates.

The following is a nonexhaustive list of chemicals that should be included:

PFOA and its salts

- Octanoic acid, pentadecafluoro- (CAS 335-67-1)
- Octanoic acid, pentadecafluoro- ammonium salt (CAS 3825-26-1)

PFOA precursors

- Octane, 1,1,1,2,2,3,3,4,4,5,5,6,6,7,7, 8,8-heptadecafluoro-8-iodo- (CAS 507-63-1)
- 1-Decanol, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluoro- (CAS 678-39-7)
- 1-Decene, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluoro- (CAS 21652-58-4)
- 2-Propenoic acid, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluorodecyl ester (CAS 27905-45-9)
- 2-Propenoic acid, 2-methyl-, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluorodecyl ester (CAS 1996-88-9)
- 2-Decenoic acid, 3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-hexadecafluoro- (CAS 70887-84-2)
- Decanoic acid, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluoro- (CAS 27854-31-5)

Higher homologues

- Dodecane, 1,1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12-pentacosafluoro-12-iodo- (CAS 307-60-8)
- Decane, 1,1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10-heneicosafluoro-10-iodo- (CAS 423-62-1)
- Nonanoic acid, heptadecafluoro- (CAS 375-95-1)
- Decanoic acid, nonadecafluoro- (CAS 335-76-2)
- 1-Decanol, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluoro- (CAS 678-39-7)
- Decane, 1,1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8-heptadecafluoro-10-iodo- (CAS 2043-53-0)
- Dodecane, 1,1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10-heneicosafluoro-12-iodo- (CAS 2043-54-1)
- 2-Propenoic acid, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluorodecyl ester (CAS 4980-53-4)
- 2-Propenoic acid, 2-methyl-, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,12-heneicosafluorododecyl ester (CAS 17741-60-5)

B. ANALYTICAL METHODS

Analyses should be conducted using the most accurate instrumentation and procedures available as of the time of testing. Please provide detailed information on the methods used (including analytical standards used, sampling, sample treatment, analysis), assumptions made, uncertainties and detection limits (LOD, LOQ) for the data provided.

Appendix E

Draft Company Report: Summary of Baseline Emissions and Product Content

2010/15 PFOA Global Stewardship Program

Draft Company Report: Summary of Baseline Emissions and Product Content

SECTION 1: REPORT DATE	October 2006

SECTION 2: COMPANY IDENTIFICATION	
2a	Company Name
	Street Address

SECTION 3: SUMMARY OF EMISSIONS					
Reporting Period (use calendar year - e.g. Jan 1, 2000 to Dec 31, 2000)					
3a	Operations	Chemical category	Releases to all environmental media from fluoropolymer and telomer manufacture		
			kgs	$\frac{\text{kgs of category}}{\text{kgs of fluoropolymers}}$[1]	$\frac{\text{kgs of category}}{\text{kgs of telomers}}$
	U.S. facilities	PFOA and PFOA salts			
		Higher homologues			
		Precursors			
3b	Non-U.S. facilities	PFOA and PFOA salts			
		Higher homologues			
		Precursors			
3c	Please provide information on the methods, assumptions, uncertainties and detection limits for the data provided above.				

SECTION 4: SUMMARY OF PRODUCT CONTENT					
Reporting Period (use calendar year - e.g. Jan 1, 2000 to Dec 31, 2000)					
4a	Product type		Fluoropolymer dispersions	Other fluoropolymers[1]	Telomer based products
	Production volume (kgs/year)[2]				
4b	Operations	Chemical category	Concentration[3]		
			Fluoropolymer dispersions[4] (ppm wet-weight)	Other fluoropolymers[1,5] (ppb dry-weight)	Telomer based products[6] (ppb dry-weight)
	U.S. facilities	PFOA, PFOA salts and higher homologues			
		Precursors			
4c	Non-U.S. facilities	PFOA, PFOA salts and higher homologues			
		Precursors			
4d	Please provide information on the methods, assumptions, uncertainties and detection limits for the data provided above.				

---

[1] Fluoropolymers manufactured with PFOA.

[2] Use the following ranges: (1) Zero (2) > 0 – 10 kgs; (3) > 10 kgs – 100 kgs; (4) > 100 kgs – 1,000 kgs; (5) > 1,000 kgs – 10,000 kgs; (6) > 10,000 kgs – 100,000 kgs; (7) > 100,000 kgs – 1,000,000 kgs; (8) Over 1,000,000 kgs.

[3] Concentration should reflect the concentration of chemical in the product as sold by the reporting company. If the reporting company has information concerning the concentration of chemical in the product as used by others – for example, as incorporated by dilution into a formulation – that additional information would also be helpful.

[4] This value should be expressed as a weighted average concentration and range.

[5] This value should be expressed as a maximum concentration.

[6] This value should be expressed as a simple (not weighted) average and range.

Appendix F

Draft Company Annual Report: Summary of Reductions in Emissions and Product Content

2010/15 PFOA Global Stewardship Program

Draft Company Report: Summary of Reductions in Emissions and Product Content

SECTION 1: REPORT DATE	October 20__

SECTION 2: COMPANY IDENTIFICATION	
2a	Company Name
	Street Address

SECTION 3: SUMMARY OF EMISSIONS						
Reporting Period (use calendar year - e.g. Jan 1, 2005 to Dec 31, 2005)						
3a	Operations	Chemical category	Releases to all environmental media from fluoropolymer and telomer manufacture			% Reduction of total kgs released from baseline year
			kgs	$\frac{\text{kgs of category}}{\text{kgs of fluoropolymers}^{1}}$	$\frac{\text{kgs of category}}{\text{kgs of telomers}}$	
	U.S. facilities	PFOA and PFOA salts				
		Higher homologues				
		Precursors				
3b	Non-U.S. facilities	PFOA and PFOA salts				
		Higher homologues				
		Precursors				
3c	Please provide information on the methods, assumptions, uncertainties and detection limits for the data provided above.					

<table>
<tr><th colspan="9">SECTION 4: SUMMARY OF PRODUCT CONTENT</th></tr>
<tr><td colspan="5">Reporting Period (use calendar year - e.g. Jan 1, 2005 to Dec 31, 2005)</td><td colspan="4"></td></tr>
<tr><td rowspan="2">4a</td><td colspan="2">Product type</td><td colspan="2">Fluoropolymer dispersions</td><td colspan="2">Other fluoropolymers[1]</td><td colspan="2">Telomer based products</td></tr>
<tr><td colspan="2">Production volume (kgs/year)[2]</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td rowspan="4">4b</td><td rowspan="2">Operations</td><td rowspan="2">Chemical category</td><td colspan="3">Concentration[3]</td><td colspan="3">% Reduction from baseline year</td></tr>
<tr><td>Fluoropolymer dispersions[4] (ppm wet-weight)</td><td>Other fluoropolymers[1,5] (ppb dry weight)</td><td>Telomer based products[6] (ppb dry weight)</td><td>Fluoropolymer dispersions</td><td>Other fluoropolymers[1]</td><td>Telomer based products</td></tr>
<tr><td rowspan="2">U.S. facilities</td><td>PFOA, PFOA salts and higher homologues</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Precursors</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">4c</td><td rowspan="2">Non-U.S. facilities</td><td>PFOA, PFOA salts and higher homologues</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Precursors</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">4d</td><td colspan="8">Please provide information on the methods, assumptions, uncertainties and detection limits for the data provided above.</td></tr>
<tr><td colspan="8"></td></tr>
</table>

---

[1] Fluoropolymers manufactured with PFOA.

[2] Use the following ranges: (1) Zero (2) > 0 – 10 kgs; (3) > 10 kgs – 100 kgs; (4) > 100 kgs – 1,000 kgs; (5) > 1,000 kgs – 10,000 kgs; (6) > 10,000 kgs – 100,000 kgs; (7) > 100,000 kgs – 1,000,000 kgs; (8) Over 1,000,000 kgs.

[3] Concentration should reflect the concentration of chemical in the product as sold by the reporting company. If the reporting company has information concerning the concentration of chemical in the product as used by others – for example, as incorporated by dilution into a formulation – that additional information would also be helpful.

[4] This value should be expressed as a weighted average concentration and range.

[5] This value should be expressed as a maximum concentration.

[6] This value should be expressed as a simple (not weighted) average and range.

Instructions for Reporting PFAS Under TSCA Section 8(a)(7)

U.S. Environmental Protection Agency Office of Pollution Prevention and Toxics
May 2024
EPA-705-G-2023-3727

NMOGA Exhibit D7

DOCUMENT HISTORY

Document Date	Action
October 2023	Creation of original document and posting to docket and TSCA website
April 2024	Clarifying revisions to Section 2.1.2: Is Your Chemical a PFAS? Removal of references to online reporting guide Edits to Section Byproduct Reporting section to clarify CBI substantiation questions Revisions to Appendix C: Examples of PFAS covered by this rule

HIGHLIGHTS OF REPORTING AND RECORDKEEPING REQUIREMENTS FOR PFAS UNDER TSCA 8(a)(7)

- Reporting is required for any manufacturer (including importer) of a per- or polyfluoroalkyl substance (PFAS).
- Reporting is required for all PFAS, as defined in 40 CFR 705, that are chemical substances as defined by TSCA, that have been manufactured (including imported) for commercial purposes during this rule's lookback period.
- Information on the reportable chemical substance must be reported during the data submission period (40 CFR 705).
- All reporting sites must report PFAS data electronically, using the section 8(a)(7) web-based reporting tool within EPA's Central Data Exchange (CDX) system. Prior to submitting data, submitters must register with CDX. Ensure that your pop-up blocker is disabled before you begin to use the PFAS section 8(a)(7) tool to complete your form.
- Streamlined reporting is available for importers of articles and for manufacturers of less than 10 kg of a substance used solely for research and development.
- No small manufacturer exemptions are in effect for this data call. You may be required to report under this PFAS data call even if you are not required to report to under other TSCA requirements such as CDR due to a small manufacturer exemption.
- Information submitted under this data call may be claimed as confidential; however, such claims must be made at the time of submission and substantiated in accordance with TSCA and the PFAS data reporting rule. Submitters must provide upfront substantiation of all confidentiality claims except for claims made for import or yearly production volume information. Submitters who do not know the underlying identity of the chemical other than a generic chemical name (i.e., do not know a CASRN, or TSCA Accession or LVE numbers) are not required to assert and substantiate a CBI claim for chemical identity. Reporters using the article importer form also are not required to assert and substantiate a CBI claim for specific chemical identity. Certain processing and use data elements or a response that is designated as "not known or reasonably ascertainable" may not be claimed as confidential (40 CFR 705.30).
- Visit the section 8(a)(7) rule website (*https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/tsca-section-8a7-reporting-and-recordkeeping*) for other guidance materials and contact information for technical assistance.

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

PREFACE

The primary goal of this document is to help the regulated community comply with the requirements of the TSCA Section 8(a)(7) Reporting and Recordkeeping Requirements for Perfluoroalkyl and Polyfluoroalkyl Substances rule, hereafter referred to as section 8(a)(7) reporting. This document does not substitute for that rule, nor is it a rule itself. It does not impose legally binding requirements on the regulated community or on the U.S. Environmental Protection Agency (EPA).

Manufacturers (including importers) are required by the section 8(a)(7) rule to report to EPA information concerning the manufacturing, use, disposal, and environmental and health effects of certain Perfluoroalkyl or Polyfluoroalkyl Substances (PFAS). Manufacturers (including importers) are subject to the reporting requirements based on manufacturing (including importing) activities conducted since January 1, 2011. This is a one-time reporting event to provide greater transparency on the uses and risks associated with PFAS and is mandated by the Fiscal Year 2020 National Defense Authorization Act (NDAA).

Data submissions are due by the close of the submission period. The submission period will begin twelve months following the effective date of the final rule and will last for six months. PFAS manufacturers will have 18 months from the effective date of the rule to report: May 8, 2025. For small manufacturers (using the same definition as 40 CFR 704.3) whose PFAS reporting obligations are exclusively due to article import, the submission period will last twelve months, such that all reporting from these small article importers is due two years from the effective date of the final rule: November 10, 2025. Data must be submitted using the "TSCA section 8(a)(7) PFAS data call rule" service via EPA's Central Data Exchange (CDX), hereafter referred to as the "reporting tool." Submitters are required to use the reporting tool to prepare their submissions. The reporting tool guides users through a "hands-on" process of creating an electronic submission. A user guide on how to register for CDX and access the reporting tool is available on the *TSCA section 8(a)(7) Reporting and Recordkeeping Requirements for Perfluoroalkyl and Polyfluoroalkyl Substances* website at *https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/tsca-section-8a7-reporting-and-recordkeeping*.

This instructions document contains the following chapters and appendices:

- Chapter 1 – Introduction to the TSCA section 8(a)(7) PFAS reporting rule.
- Chapter 2 – Reporting requirements to determine which chemical substances are reportable, who must report, and what information must be reported.
- Chapter 3 – When you must report.
- Chapter 4 – Instructions for completing section 8(a)(7) reporting.
- Chapter 5 – How to obtain copies of documents cited in this Instructions document.
- Appendix A – Glossary.
- Appendix B – Key Comparisons between Section 8(a)(7) Data Call and CDR

- Appendix C – Examples of PFAS covered by this rule.
- Appendix D – Descriptions of codes for reporting *Processing or Use Operations, Industrial Sectors, Industrial Function Categories,* and *Consumer and Commercial Product and Function Categories*.

1. Introduction

1.1 Background and Statutory Authority

In accordance with obligations under TSCA section 8(a)(7), as amended by the National Defense Authorization Act for Fiscal Year 2020, EPA is requiring persons that manufacture (including import) or have manufactured these chemical substances for commercial purposes in any year since January 1, 2011, to submit information to EPA regarding PFAS uses, production volumes, byproducts, disposal, exposures, and existing information on environmental or health effects.

This document provides detailed information and examples to assist manufacturers (including importers) in reporting under TSCA section 8(a)(7). Appendix A of this document provides a glossary of terms, which may help you to understand the reporting requirements.

This document is not a substitute for the TSCA section 8(a)(7) PFAS rule in 40 CFR Part 705. To the extent that any inconsistencies exist between the section 8(a)(7) rule and this document, the requirements as promulgated in the rule should be followed. You should carefully review 40 CFR Part 705 and the final rule preamble (available in this rule's docket at *www.regulations.gov*; docket ID EPA-HQ-OPPT-2020-0549) to determine whether you are required to report information under the section 8(a)(7) rule.

1.2 Duplicative reporting

Your site may have already reported some section 8(a)(7) data to EPA through another EPA program. If that is the case, the site should determine whether EPA has identified such reporting as "duplicative" in the section 8(a)(7) rule. If EPA has identified the reporting as duplicative, your site is not required to re-report duplicative information, but must submit a report and include all information required by this data call that has not been previously reported to EPA. Information that has been reported for some but not all years from 2011 to 2022 must be reported for the "missing" years. Information that has been previously reported, but not to the level of detail required by this data call, or using exemptions not applicable to this data call, must be reported under this data call to the level of detail required, if known to or reasonably ascertainable by you. In the event that new, more accurate, or more detailed information has become known to or reasonably ascertainable by the site, that information must be reported under this data call.

The electronic reporting system will allow you to indicate that certain information has already been reported to EPA. EPA has identified data elements that could have been previously reported under Chemical Data Reporting (CDR); Toxics Release Inventory (TRI) reporting, also known as section 313 of the Emergency Planning and Community Right-to-Know Act (EPCRA 313); Greenhouse Gas Reporting (GHGRP); and TSCA sections 8(d) and 8(e). Additionally, there may be limited overlap between forms submitted under section 8(a)(7) reporting in the event that a reportable PFAS is produced as a byproduct during manufacture, processing, or disposal of another reportable PFAS.

The section 8(a)(7) reporting software will identify the data elements that could contain information already reported to EPA. For these data elements, you may indicate if your company has already reported the information to EPA. You must clearly indicate where the information can be found (i.e., which reporting program) and when that information was submitted (i.e., which year). **Information must have been reported *as required by the section 8(a)(7) rule***; for example, other programs may have exemptions, such as for articles or impurities, that could mean information reported to those programs was not reported as required by this data call.

EPA anticipates that the primary program with “duplicative reporting” is Chemical Data Reporting (CDR). Two other EPA programs that have minor overlap with section 8(a)(7) include the Toxics Release Inventory (TRI) and the Greenhouse Gas Reporting Program (GHGRP).

Note, however, that these programs both cover only a limited subset of the PFAS covered by section 8(a)(7) and have thresholds for reporting that do not apply to this data call. Therefore, you may be required to report under this data call even if you were not required to report under TRI or GHGRP. Further, due to differences in how data are to be reported to those programs, reporting to TRI or GHGRP may not fulfill the requirements of this data call. Some health or environmental information may also have been reported under TSCA section 8(d) or TSCA section 8(e) or another authority.

Note that information reported on pre-manufacture notices (PMNs) or low volume exemptions (LVEs) generally does not fulfill requirements under section 8(a)(7), as PMNs and LVEs reflect information before manufacture of a substance commences.

Information reported to entities other than EPA, such as state agencies, or provided to EPA outside a formal EPA reporting program (such as comments provided on a proposed rule), ***does not*** fulfill your requirement to report to EPA under section 8(a)(7) and cannot be cited as duplicative reporting.

EPA expects that even when a company has previously reported some section 8(a)(7) information, that information will constitute only a minority of information to be reported under this data call.

Information that may have previously been reported under CDR includes:

(1) Physical state of the PFAS pursuant to § 711.15(b)(3)(C)(ix);

(2) Industrial processing and use type, sector(s), functional category(ies), and percent of production volume for each use, pursuant to § 711.15(b)(4)(i)(A) through (D);

(3) Consumer and/or commercial indicator, product category(ies), functional category(ies), percent of production volume for each use, indicator for use in

products intended for children, and maximum concentration in the product, pursuant to § 711.15(b)(4)(ii)(A) through (F);

(4) Number of workers reasonably likely to be exposed for each combination of industrial processing or use operation, sector, and function, pursuant to § 711.15(b)(4)(i)(F), and the number of commercial workers reasonably likely to be exposed when the substance is used in a commercial product, pursuant to § 711.15(b)(4)(ii)(G).

Information that may have been reported to TRI includes:[1,2]

(1) Total volume recycled on-site
(2) Description of disposal process(es)
(3) Total volume released to land
(4) Total volume released to water
(5) Total volume released to air
(6) Total volume incinerated on site[3]

Information that may have been reported to GHGRP includes:[1]

(1) Production volume (imported)
(2) Volume directly exported
(3) Total volume incinerated on site

---

[1] Due to differences in reporting requirements, exemptions, and other programmatic requirements, reporting to TRI and GHGRP may not meet the requirements of TSCA section 8(a)(7). Carefully review any previous TRI or GHGRP submissions and calculation methods to determine if you may claim duplicative reporting. You may claim duplicative reporting for TRI and/or GHGRP only if the data were reported ***as required by the section 8(a)(7) rule*.**

[2] Only certain PFAS chemicals are reportable under TRI. Most PFAS were added to the TRI chemical list for 2020 reporting, while some chemicals meeting the definition of PFAS used for PFAS 8(a)(7) reporting have been reportable since before 2011. Note that the TRI chemical list includes certain chemicals as unspecified isomers, such as dichloropentafluoropropane, which could include both chemicals considered to be PFAS and chemicals not considered to be PFAS. In the event you know which isomer(s) were used at the site, you must report the specific isomers for PFAS 8(a)(7) reporting and may not consider reporting to TRI under a mixed isomer listing as duplicative.

[3] Carefully review any incineration data reported to TRI to determine if it is duplicative. To claim duplicative reporting, EPA must be able to determine the total volume of the chemical incinerated on site. EPA anticipates that many reporters' TRI reports will not fulfill the requirements of Section 8(a)(7) for the total volume incinerated on site.

Information that may have been reported under TSCA section 8(d) or 8(e) or another authority includes:

(1) Environmental and health effects (OECD harmonized template)

(2) Environmental and health effects study report

(3) Environmental and health effects supporting information

Table 1-1Table 1-1 shows some examples of how companies may consider prior reporting.

Table 1-1. Examples of prior reporting impacts on PFAS data call reporting

Previous Reporting	Site section 8(a)(7) responsibilities
A manufacturer previously reported on Example PFAS A under 2020 CDR. That report included information required by section C of this data call, from 2016 through 2019. Most information required by section C was reported for only the principal reporting year, 2019, and some information for section C was reported for 2016-2018. The site started manufacturing the PFAS in 2015 but did not meet the CDR reporting threshold for that year. The manufacturer continued to produce Example PFAS A in the years since its last CDR report.	The manufacturer considers whether any exemptions applied to the prior CDR reporting that are not available under this rule. The manufacturer determines that the data previously submitted to CDR did not exempt any activities or quantities that would be reportable under this rule, and therefore may be considered duplicative. For section C, the manufacturer indicates that data were already reported to CDR for the applicable fields for 2019, completing the fields for "site-limited?" and recycling, which are not reported to CDR. The manufacturer also indicates the data were already reported to CDR for the fields that were reported for 2016-2018. The manufacturer fills in the remaining section C information for 2016-2018 and all section C information for 2015 and 2020-2022. The manufacturer fills in information for 2015-2022 in all other sections of its PFAS data call reports, as that information has not been reported to EPA for any year.
A manufacturer previously reported information about Example PFAS B, which was manufactured from 2012-2015, to the 2016 CDR. At the time of 2016 CDR submission, several required data fields were not known to or reasonably ascertainable by the company (NKRA). However, the company since learned additional information about the chemical.	The manufacturer indicates duplicative reporting for the data that was known to the site and submitted to EPA for 2012-2015. The manufacturer must report newly acquired information to this PFAS data call for fields reported as "NKRA" to CDR for 2012- 2015. The manufacturer may indicate duplicative reporting for remaining fields that were originally reported as "NKRA" and for which the manufacturer has not acquired new information.
Example Company C manufactures Example PFAS C and has begun gathering and compiling information about this chemical for 2024 CDR (for activities from 2020-2023). The company's 2024 CDR report will not be submitted before the end of the section 8(a)(7) submission period.	The company must report the 2020-2022 information under section 8(a)(7) reporting, even if the information will be reported to EPA in the future. EPA encourages submitters to review their in- progress CDR submissions in gathering data for section 8(a)(7) submissions, and vice versa, to reduce overall reporting

Previous Reporting	Site section 8(a)(7) responsibilities
	burden.
Example Company D imported Example PFAS D at one site in 2015. 10,000 pounds of Example PFAS D was imported as a component of an article, and 50,000 pounds was imported in a mixture. The company reported Example PFAS D to CDR for 2015, reporting on the 50,000 pounds imported in the mixture. The company did not consider the 10,000 pounds of Example PFAS D imported as articles, which are exempt for CDR reporting.	The company must newly report all information for Example PFAS D under this data call. Because information reported to CDR excluded quantities imported in articles, which are not exempt under this data call, the information was not previously reported as required by this data call. The site may not indicate duplicative reporting.
Example Company E imported an article containing Example PFAS E in 2012, 2013, and 2017, but has not been previously required to report this information to any EPA programs. The site reported information about this chemical to the state of Washington's Department of Ecology pursuant to the state's requirements for chemicals in children's products.	The company must report to EPA all information required by this data call for 2012, 2013, and 2017, and indicate that Example PFAS E was not produced in the other years. Reporting to a state program does not fulfill or reduce any requirements for reporting under this PFAS data call.
Example Company F manufactured 1,000 pounds of Example PFAS F each year during 2019, 2020, and 2021. Example PFAS F was added to the TRI chemical list for 2020 reporting and was not TRI-reportable for 2019. Each year, 50 pounds of the PFAS were manufactured and used for quality control in a laboratory on-site. All Example PFAS F produced at Example Company D was disposed of in the site's on-site landfill. After determining that the quantity of Example PFAS F used in the laboratory was exempt from TRI reporting, Company C reported 950 pounds of Example PFAS F releases to TRI for 2020 and 2021.	The company must report all information about Example PFAS F for 2019, because no TRI report was filed for that year. The site may not indicate duplicative reporting for release quantities for 2020 and 2021, because the quantities reported to TRI excluded laboratory uses that are not exempt under Section 8(a)(7) reporting. The company instead reports 1,000 pounds of land disposal for 2020 and 2021. The company may indicate duplicative reporting for types of disposal processes and the quantities released to air, water, and recycled on-site.

2. Reporting Requirements

PFAS data reporting rule requirements apply to certain persons that manufacture (including import) or have manufactured PFAS in any year since January 1, 2011. The term "PFAS" is defined in Appendix A and examples of PFAS are provided in Appendix B. Please note that any use of the term "manufacture" in this document will encompass "import" and the term "manufacturer" will encompass "importer."

For reporting to the PFAS data reporting rule, manufacturers (including importers) are required to use the section 8(a)(7) reporting tool via EPA's CDX to submit information in response to the requirements of the section 8(a)(7) rule (40 CFR Part 705). You must register with CDX to submit online, and you must register the name of the company on whose behalf you are submitting. EPA does not accept paper submissions or electronic media (diskette, CD-ROM, etc.) for any section 8(a)(7) submission (40 CFR 705).

Note that many aspects of reporting for this PFAS data reporting rule are similar to Chemical Data Reporting (CDR), but there are important differences. Even if you have reported previously under the CDR or were exempt from reporting under CDR, you should carefully review the reporting requirements for this rule to ensure you report correctly. Key comparisons between section 8(a)(7) and CDR are outlined in Appendix B of this document.

You should consider the following three steps to determine whether you are required to report for each PFAS chemical substance that you domestically manufacture (including import) into the United States **during each year since** 2011 (i.e., consider calendar years 2011 through 2022):

- Step I: Is your chemical substance subject to PFAS 8(a)(7)?
- Step II: Do you qualify for streamlined reporting?
- Step III: What information must you report?

This chapter discusses each of these steps and the associated reporting requirements in more detail.

2.1 Step I: Is Your Chemical Substance Subject to section 8(a)(7)?

For the purposes of the section 8(a)(7) Reporting Rule, *per- and polyfluoroalkyl substances* or *PFAS* means any chemical substance that contains at least one of these three structure units:

1) $R\text{-}(CF_2)\text{-}CF(R')R''$, where both the CF_2 and CF moieties are saturated carbons
2) $R\text{-}CF_2OCF_2\text{-}R'$, where R and R' can either be F, O, or saturated carbons
3) $CF_3C(CF_3)R'R''$, where R' and R" can either be F or saturated carbons.

This definition may not be identical to other definitions of PFAS used within EPA and/or other organizations. See Section 2.1.2 for further description of these structures. To assist potential reporters with determining whether certain substances may be covered under this structural definition, EPA has identified specific PFAS covered by this rule. This non-exhaustive list is available in EPA's CompTox Dashboard (*https://comptox.epa.gov/dashboard/chemical-lists/PFAS8a7*) and a limited version including only chemicals on the public TSCA Inventory or with low-volume exemptions is included as Appendix B in this guidance document.

Note that the manufacture of PFAS as a byproduct, an impurity, or a non-isolated intermediate **is not** exempt for the purpose of this rule, unlike CDR reporting. However, because entities that import of municipal solid wastes (MSW) for the purpose of disposal or destruction cannot know or reasonably ascertain that they imported PFAS in the MSW streams, these waste management activities are not within the scope of this rule's reporting requirements. Per 40 CFR 705.15, "reporting under this part is not required for the import of municipal solid waste streams for the purpose of disposal or destruction of the waste."

2.1.1 Is Your Chemical Substance Manufactured for Commercial Purposes During the Reporting Period?

The first step in determining your reporting requirements is to determine whether you meet the definition of manufacture or manufacturer. The following manufacturing-related terms are defined below:

- ***Manufacture*** – To import into the customs territory of the United States (as defined in general note 2 of the Harmonized Tariff Schedule of the United States), produce, or manufacture for commercial purposes. (40 CFR 705.3)
- ***Manufacture for commercial purposes*** – (1) To import, produce, or manufacture with the purpose of obtaining an immediate or eventual commercial advantage for the manufacturer, and includes among other things, such "manufacture" of any amount of a chemical substance or mixture:
  - (i) For commercial distribution, including for test marketing.
  - (ii) For use by the manufacturer, including use for product research and development, or as an intermediate.

  (2) Manufacture for commercial purposes also applies to chemical substances that are produced coincidentally during the manufacture, processing, use, or disposal of another chemical substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that chemical substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose (40 CFR 705.3).

For purposes of section 8(a)(7) reporting, a chemical substance is manufactured (including imported) only if it is domestically produced or imported for commercial purposes. See TSCA section 8(f), TSCA section 3(9), and 40 CFR 704.3, which includes a parallel definition of "Import for commercial purposes." In the case of chemical substances manufactured (including imported) by one person on behalf of another person, the manufacturer is the person actually manufacturing the chemical substance.

As identified above, the term *manufacture for commercial purposes* means that the chemical substance is produced for the purpose of obtaining an immediate or eventual commercial advantage. Manufacture for commercial purposes also applies to chemical substances that are produced coincidentally during the manufacture, processing, use, or disposal of another chemical substance or mixture, including both byproducts that are separated and impurities that remain in a chemical substance or mixture (40 CFR 705.3). Certain activities are not considered "manufacture for a commercial purpose" (e.g., non-commercial R&D activities such as scientific experimentation, research, or analysis conducted by academic, government, or independent not-for-profit research organizations, unless the activity is for eventual commercial purposes) and are not subject to the reporting requirements in this rule.

2.1.1.1 Changes to Company Ownership or Legal Identity

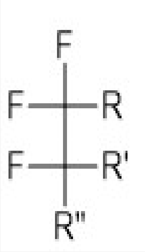
Under 40 CFR 705, the reporting obligation falls to the "person who manufactured (including imported)" a chemical substance that is a PFAS. EPA recognizes that in some cases, business transactions occurring during the reporting period have led to questions about who is now the "person who manufactured." The scenarios in *Fact Sheet: Reporting After Changes to Company Ownership or Legal Identity* are intended to serve as a general aid in appropriately resolving these questions, but they will not necessarily account for all the relevant circumstances of a particular transaction (*note that while this fact sheet was developed for CDR, changes in company ownership or legal identity are to be handled the same for section 8(a)(7) reporting as for CDR)*. It is ultimately the manufacturer's responsibility to report appropriately under this data call, notwithstanding the complexity of its own business transactions.

2.1.2 Is Your Chemical Substance a PFAS?

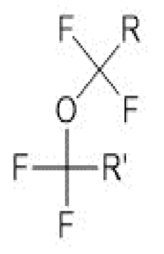
For the purposes of this action, the definition of PFAS includes any chemical substance that structurally contains at least one of the following three sub-structures. Note that in these formulas, R refers to the atom directly adjacent to the backbone:

1) $R\text{-}(CF_2)\text{-}CF(R')R''$, where both the CF_2 and CF moieties are saturated carbons (since the R groups are not defined, R, R', and R'' may be any substituent).
2) $R\text{-}CF_2OCF_2\text{-}R'$, where R and R' can either be F, O, or saturated carbons (i.e., R and R' may be any of the following: a fluorine atom, an alcohol or ether; or any substituent bonded to the backbone by a saturated carbon atom such as a CH_2 group).

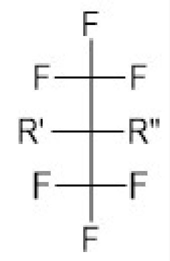
3) $CF_3C(CF_3)R'R''$, where R' and R" can either be F or saturated carbons (i.e., R' and R" may be a fluorine atom or any substituent bonded to the backbone by a saturated carbon atom such as a CH_2 group).



where R, R', R'' = any substituent
Structure 1



where R, R' = F, O, or $CR_1R_2R_3$
Structure 2



where R', R'' = F, or $CR_1R_2R_3$
Structure 3

This definition may not be identical to other definitions of PFAS used within EPA and/or other organizations. To assist potential reporters with determining whether certain substances may be covered under this structural definition, EPA has identified specific PFAS covered by this rule. This non-exhaustive list is available in EPA's CompTox Dashboard and a limited version including only chemicals on the public TSCA Inventory or with low-volume exemptions as of the publication of this guidance document is included as Appendix B in this guidance document. Note that the CompTox list may change as chemicals are added to the Dashboard.

Manufacturers must consider all manufacturing activities during the reporting period, which begins January 1, 2011. If a manufacturer has manufactured PFAS for commercial purposes in any year since January 1, 2011, they would be required to report under this rule even if they are not currently manufacturing PFAS.

This rule is limited to manufacturers (including importers) of PFAS that are considered a "chemical substance" under TSCA section 3(2). This rule does not require reporting on activities that are excluded from the definition of "chemical substance" in TSCA section 3(2)(B).

Under TSCA section 3(2), "chemical substance" means any organic or inorganic substance of a particular molecular identity, including (1) any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature, and (2) any element or uncombined radical. This rule does not require reporting on activities that are excluded from the definition of "chemical substance" in TSCA section 3(2)(B). The term "chemical substance" does not include: "(i) any mixture, (ii) any pesticide (as defined by the

Federal Insecticide, Fungicide, and Rodenticide Act) when manufactured, processed, or distributed in commerce for use as a pesticide, (iii); tobacco or any tobacco product, (iv) any source material, special nuclear material, or byproduct material (as such terms are defined in the Atomic Energy Act of 1954 and regulations issued under such Act), (v) any article the sale of which is subject to the tax imposed by Section 4181 of the Internal Revenue Code of 1954 (determined without regard to any exemptions from such tax provided by section 4182 or 4221 or any other provision of such Code) and any component of such an article (limited to shot shells, cartridges, and components of shot shells and cartridges), and (vi) any food, food additive, drug, cosmetic, or device, as defined in section 201 of the Federal Food, Drug, and Cosmetic Act, when manufactured, processed, or distributed in commerce for use as a food, food additive, drug, cosmetic or device" [15 USC 2602(2)(B)].

Even though the definition of chemical substance excludes mixtures, PFAS as a chemical substance may be present in a mixture. Therefore, this rule requires reporting on each chemical substance that is a PFAS, including as a component of a mixture. This rule does not require reporting on components of a mixture that do not fall under the structural definition of PFAS.

2.2 Step II: Do You Qualify for Streamlined Reporting?

If you determined from Step I that you manufacture (including import) a reportable PFAS for commercial purposes, Figure 2-1Figure 2-1 presents a decision logic diagram that may help you determine whether you are a manufacturer (including importer) who must report with the Standard Form or if you may qualify for streamlined reporting. The following subsections explain each question in greater detail. Note that unlike CDR reporting, no reporting exemptions apply to section 8(a)(7).

2.2.1 Did you import an article containing a reportable PFAS?

If you imported an article containing PFAS, you may use a streamlined Article Import form. This streamlined form does not require all information required for the standard form; when you select "article import reporting" in the section 8(a)(7) reporting tool, the program will show only fields required for this streamlined reporting. Only certain fields in Sections A, B, and C are required for the streamlined article importing. Further, because importers may not know or be able to ascertain how much PFAS is contained within the articles, the article import form allows production volume to reported as the total weight of the imported articles or as the quantity of articles imported (see Section 4.7.2.24.7.2.2), rather than weight of the PFAS. If you have any additional information, such as an SDS or information about disposal, report that information in the Optional Information section of the form (see Section 4.12).

Some sites may both import a PFAS in an article and otherwise manufacture the same PFAS (i.e., domestically manufacture or import other than in an article). In that case, you may choose to either report the imported article and otherwise manufactured PFAS separately, using the streamlined article import form for the imported article and using the standard form for the otherwise manufactured PFAS, or you may include the information for the imported article within the standard form, submitting one standard form for all PFAS produced and imported by the site.

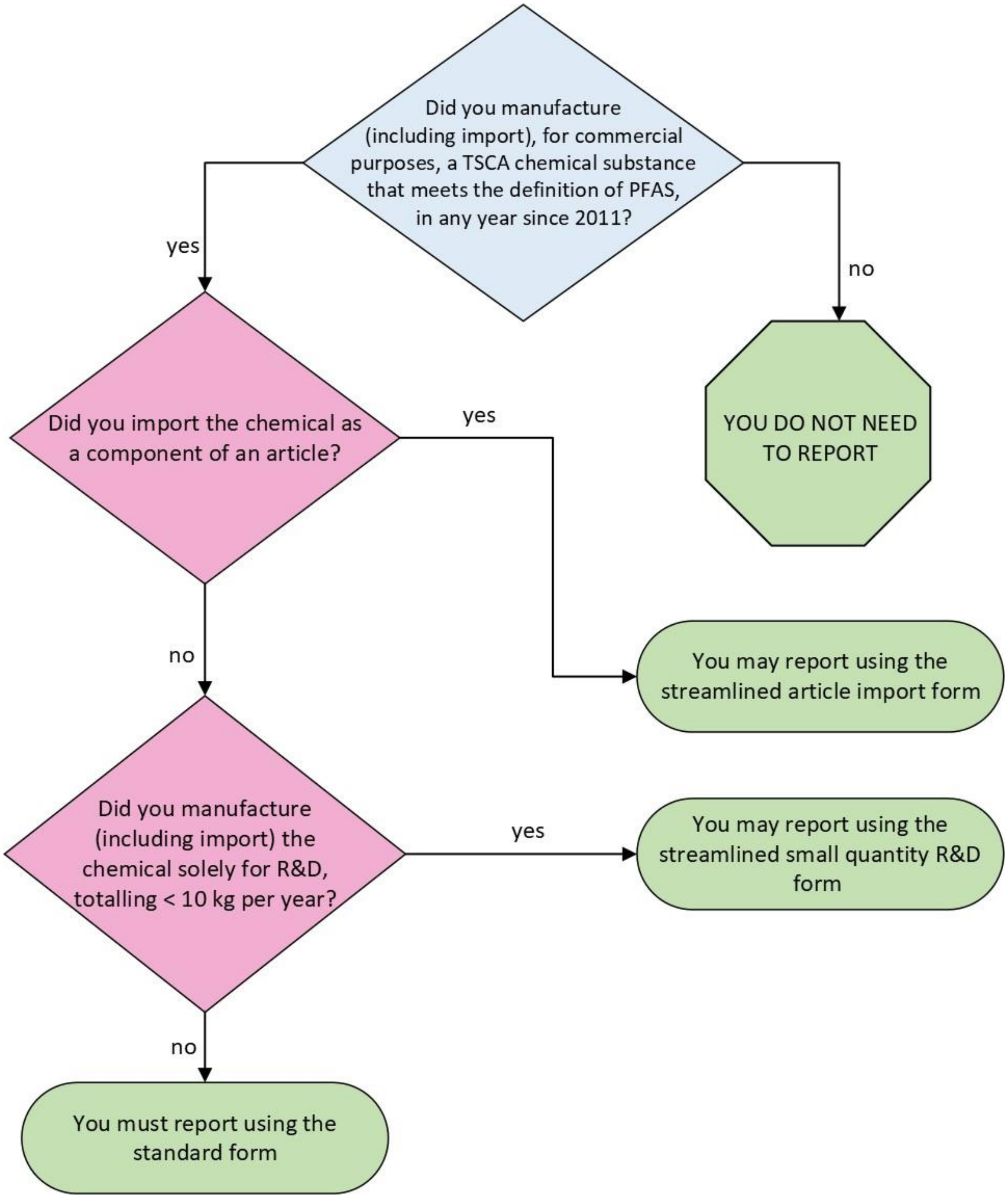


Figure 2-1. Decision Logic Diagram for Evaluating Step II

If you are unsure whether you are importing an article, refer to the CDR "Imported Articles" factsheet at *https://www.epa.gov/chemical-data-reporting/tsca-chemical-data-reporting-fact-sheet-imported-articles-2020*. The TSCA definition of an article is the same for both CDR reporting, as referenced in this factsheet, and for PFAS section 8(a)(7) reporting (40 CFR 705.3). However, recall that while importing an article is exempt from CDR, it is **not** exempt from section 8(a)(7) reporting. If you import an article containing a chemical substance that is a PFAS, you may be eligible to use the streamlined Article Import form, but you **are not** exempt from reporting. You have until May 8, 2025, to report. However, if you meet the following two criteria, you have until November 10, 2025, to report: (1) are considered a small manufacturer pursuant to 40 CFR 704.3 (see Appendix A); and (2) have reporting obligations under this rule exclusively due to importing articles.

2.2.2 Did you manufacture a reportable PFAS in quantities below 10 kg per year exclusively for purposes of research and development (R&D)?

Persons who manufacture (including import) PFAS in small quantities solely for research or analysis for commercial purposes may report using the streamlined small quantity R&D form. The streamlined small quantity R&D form requires reporting only of the chemical substance identification information (see Section 4.3), domestic manufacture and imported volumes, indication of whether the substance was imported but never on site, and an optional additional information field.

Note that any PFAS manufactured for commercial purposes is reportable under this data call. "Manufacture for commercial purposes" encompasses any importing, production, or other manufacturing activities with the purpose of obtaining an immediate or eventual commercial advantage and includes chemicals "for use by the manufacturer, including use for product research and development." R&D substances which meet the scope of "manufactured for commercial purposes" are to be reported under this rule, even if the PFAS itself was not later commercialized. See Section 2.1.12.1.1 for additional guidance on determining if a PFAS was manufactured for commercial purposes."

Some sites may both manufacture a PFAS in small quantities for R&D and otherwise manufacture the same PFAS (i.e., domestically manufacture or import). In that case, your site does not qualify for use of the streamlined form. The streamlined form is limited to persons manufacturing (including importing) PFAS ***solely*** for research or analysis.

Example 2-1. Example Company G produces Example PFAS G at one site. Example PFAS G was produced in amounts of 3 kg in 2011, 7 kg in 2012, and 6 kg in 2013. Example PFAS G was not produced during any other year since 2011 and the quantities produced were used exclusively for research and development.

Because Example PFAS G is used only for research and development, and the volume manufactured was less than 10 kg each year, Example Company G reports using the streamlined R&D form for Example PFAS G.

2.3 Step III: What Information Must You Report?

Once you determine from Steps I and II that you are a manufacturer (including importer) of a reportable PFAS and are required to report, this section will help you determine what information you must report.

If you are required to report and do not qualify for either streamlined form, you are required to report all information described in 40 CFR 705. Importers of PFAS-containing articles and manufacturers (including importers) of small R&D quantities may use streamlined forms, which include only the data elements that EPA believes will be known to or reasonably ascertainable to manufacturers in those situations. The online reporting software will guide you through the data elements required for each form.

Basic company and site identification information, (submitted on Part I of the form) is required by 40 CFR 705.15(a)(1). Chemical identification and information pertaining to the manufacture (including import) of chemical substances (described in *Part II – Section A*) is required by 40 CFR 705.15(a)(2). Note that the basic company and site information is reported once per site, while the manufacturing information is reported separately for each reportable PFAS at the site. Industrial processing and use, and consumer and commercial uses of the chemical substance (described in *Part II – Section B*) is required by 40 CFR 705.15(a)(3).

Information about byproducts (described in *Part II – Section D*) is required by 40 CFR 705.15(a)(3). Information about the environmental and health effects of the PFAS (described in *Part II – Section E*) is required by 40 CFR 705.15(f). Information about worker exposure to the PFAS (described in *Part II – Section F*) is required by 40 CFR 705.15(g). Information about the release or disposal of the PFAS (described in *Part II – Section G)* is required by 40 CFR 705.15(h).

Example 2-2. Example Company H manufactures 8 kg of Example PFAS H in 2017 for on-site R&D operations in development of a new cleaning product. The company scales up R&D for this substance and manufactures 100 kg of Example PFAS H in 2018. The company then discontinues R&D and does not ultimately commercialize Example PFAS H. Example PFAS H is not manufactured after 2018.

Example PFAS H is manufactured for commercial purposes because Example Company H manufactured the chemical with the purpose of obtaining an eventual commercial advantage, so Example Company H must report the substance, even though it was not ultimately commercialized. For 2017, the company manufactured < 10 kg of the substance for R&D and meets the requirements for the R&D form. For 2018, the company manufactured > 10 kg so exceeds the threshold for the R&D form. The company may take one of two actions:

1) Use the R&D form to report for 2017 and the standard form for 2018

2) Report for both 2017 and 2018 on one standard form, completing all fields on the form for both years.

Example 2-3. Example Company I begins importing an article containing Example PFAS I in 2017 and continues importing the article through 2022. Example PFAS I provides stain resistance in a finished textile product. Example Company I does not produce or import any other products containing Example PFAS I.

Because Example PFAS I is only imported in an article, Example Company I reports for this chemical using the streamlined article importer form.

3. When You Must Report

You are required to report information pertaining to each calendar year since January 1, 2011 through December 31, 2022, in which you manufactured a PFAS. The submission period begins twelve months after the effective date of the section 8(a)(7) final rule and lasts for six months. Therefore, reporting is due 18 months after the effective date of this final rule: May 8, 2025. Small manufacturers (per 40 CFR 704.3) whose PFAS reporting obligations are exclusively due to importing articles have an additional six months to report. These small article importers have 24 months from the effective date of the final rule to report: November 10, 2025.

Your report must be submitted to EPA using the electronic section 8(a)(7) reporting tool ("reporting tool") via EPA's Central Data Exchange (CDX) no later than the close of the submission period. You should note that registration with CDX is required prior to accessing the reporting tool to submit your PFAS data call information (40 CFR 705.35). To get you started, guides are available on EPA's website:

- CDX Registration Guide, which covers the specifics of CDX registration (https://cdx.epa.gov/About/UserGuide)

If you are required to report, failure to file your report during this period is a violation of TSCA sections 8(a) and 15 and may subject you to penalties (40 CFR 705.1).

4. Instructions for Completing Section 8(a)(7) Reporting

This chapter will help you complete section 8(a)(7) reporting. Section 4.1 describes how to certify your submission. Section 4.2 discusses the reporting standard – the effort required to comply with the PFAS data call. Sections 4.3 through 4.11.3 provide information to help you complete each required section of the reporting form.

You are required to use the section 8(a)(7) online reporting tool in CDX to complete and submit a reporting form for each reportable PFAS. If you are reporting information for more than one PFAS at your site, you must report information for each reportable PFAS on its own form. If you are reporting for multiple sites, you must submit separate forms for each site. In most cases, you will submit exactly one form per chemical at the site. However, in certain cases if you are an article importer, you may submit multiple forms for the same chemical at one site; see Section 2.22.2.

The standard reporting form is comprised of a certification statement and three parts, as follows:

- The certification statement and Part I of the form are completed once per reporting site. Part I contains company, site, and contact information, some of which is pre-populated based on the information in your CDX account for the site. Once this section has been completed for a reporting site, the reporting tool will automatically populate Part I with this information for any additional forms for the site.
- Part II – Sections A – C are completed for each reportable PFAS at the site and contains information associated with the identity, manufacture, and properties of the chemical substance.
- Part II – Section D is completed for the byproducts produced during manufacture of each PFAS.
- Part II – Section E is completed for each reportable PFAS at the site and contains information associated with the environmental and health effects of the PFAS.
- Part II – Section F is completed for each reportable PFAS at the site and contains information associated with workers' exposure to the PFAS.
- Part II – Section G is completed for each reportable PFAS at the site and contains information associated with the disposal of the PFAS.
- Part II – Section H is an optional free text field that allows submittal of any additional information.
- Part III is completed for each reportable chemical substance at the site for which confidentiality claims are made for one or more data elements, when substantiations of the confidentiality claims are required at the time of data submission.

The streamlined article import and small-quantity R&D forms reduce the number of fields to be reported. Sections D – G are not required on these forms and the requirements for Sections A – C are reduced. If any information in the omitted sections is known to you, you may report that information in the free text field in Section H.

Note: Items such as the validation page and the SRS search page will appear in separate windows. Ensure that your pop- up blocker is disabled before you begin to complete PFAS section 8(a)(7) reporting.

4.1 Certification

Your submission(s) must be certified, indicating that your submitted information has been completed in compliance with the PFAS data call requirements, such as all information known or reasonably ascertainable is submitted, and that the confidentiality claims made in this report are true and correct. To certify, the certification statement must be electronically signed and dated by an authorized official at your company. The authorized official typically is a senior official with management responsibility for the person (or persons) completing the form(s). You must include the printed name, title, and email address for the person signing the certification.

See the CDX User Guide for information on how to complete an electronic signature agreement.

This certification statement applies to all the information supplied on the form(s) for your site. The certification statements appear when the submission process has been initiated, at which time the submitter must either certify or cancel the submission process. If you are completing forms for multiple sites, one submission certification will be created and must be submitted for each site. Note that knowingly providing false or misleading information or concealing required information may be punishable by fine or imprisonment or both under TSCA section 16(b)(1).

4.2 Reporting Standard

Submitters are required to exercise certain levels of due diligence in gathering the information required by the section 8(a)(7) rule. You must report your information to the extent that the information is **known to or reasonably ascertainable by** you and your company.

The term “known to or reasonably ascertainable by” is defined in 40 CFR 705.3, meaning all information in a person’s possession or control, plus all information that a reasonable person similarly situated might be expected to possess, control, or know.

Under TSCA section 8(a), EPA may collect information associated with chemical substances to the extent that it is known to or reasonably ascertainable by the submitter. This includes, but is not limited to, information that may be possessed by employees or other agents of the company reporting under the section 8(a)(7) rule, including persons involved in the research, development, manufacturing, or marketing of a chemical substance and includes knowledge gained through discussions, symposia, and technical publications. For purposes of section 8(a)(7), the known to or reasonably ascertainable by standard applies to all the information required by the rule.

Examples of types of information that are considered to be in a person's possession or control, or that a reasonable person similarly situated might be expected to possess, control, or know include:

- Files maintained by the manufacturer, such as marketing studies, sales reports, or customer surveys,
- Information contained in standard references, such as a safety data sheet (SDS) or a supplier notification, and
- Information from the Chemical Abstracts Service (CAS) and from Dun & Bradstreet D-U-N-S®.

The hypothetical examples in Table 4-1 illustrate the anticipated application of the "known to or reasonably ascertainable" reporting standard, in the specific context of the collection of processing and use data under section 8(a)(7). Because the standard applies on a case-by case basis, however, these examples cannot substitute for a complete analysis of a submitter's particular circumstances.

This reporting standard does not confer a testing requirement on manufacturers. But, if manufacturers have previously tested their products for the presence of PFAS, then that information may be considered known to or reasonably ascertainable to them and should be submitted to EPA as appropriate.

Table 4-1. Examples of the Application of the "Known to or Reasonably Ascertainable" Reporting Standard for Processing and Use Data

Scenarios, Actions, and Outcomes
Scenario: Example Company J discovers that it has no knowledge of how a particular PFAS (Example PFAS J) is processed or used by its customers. Example Company J usually maintains marketing data documenting customers' use of its chemicals, in line with the reasonable business practices typical of comparable manufacturers, but it irrevocably lost these data for Example PFAS J due to an inadvertent computer malfunction. Example Company J has many customers, but it expects that it could substantially reconstruct this missing information by briefly contacting its largest customer and asking that customer what Example PFAS J is generally used for.
Application of KRA Reporting Standard:

If:	Then:
Example Company J contacts its largest customer and reports on the basis of the processing and use data that the customer was willing to provide.	Duties Likely Fulfilled
Example Company J did not endeavor to supplement the information it already knew.	Duties Not Fulfilled

Scenario: Example Company K has never maintained information on how a particular PFAS (PFAS K) is processed or used by its customers. However, it is typical for comparable manufacturers to collect such information as part of their reasonable business practices. Example Company K has many customers, who it believes process and use the particular PFAS in a similar manner and it expects that it could substantially fill this data gap by reviewing the public website of its largest customer.

Application of KRA Reporting Standard:

If:	**Then:**
Example Company K reviews its largest customer's website, and of the information contained on the website	Duties Likely Fulfilled
Example Company K did not endeavor to supplement the information it already knew.	Duties Not Fulfilled

Scenario: Example Company L maintains seasonal marketing data on changes in use patterns for a particular PFAS (Example PFAS L). Comparable manufacturers typically only maintain such data on an annual basis, in line with reasonable business practices. Example Company L irrevocably loses its summer marketing data for Example PFAS L, due to an inadvertent computer malfunction. Example Company L expects that it could substantially reconstruct the missing summer marketing data by contacting its largest customer and asking the customer what it used or processed Example PFAS L for in the past summer.

Application of KRA Reporting Standard:

If:	**Then:**
Instead of attempting to reconstruct the summer data by contacting its largest customer, Example Company L reports on the basis of the processing and use data that it already knows (regarding the winter, spring, and fall of the year).	Duties Likely Fulfilled
Example Company L designated the information as "not known or reasonably ascertainable" simply because one of the seasonal marketing reports was missing	Duties Not Fulfilled

Scenario: Example Company M has never maintained information on how a particular PFAS (Example PFAS M) is processed or used by its customers. However, it is typical for comparable manufacturers to collect such information as part of their reasonable business practices. Example Company M has one major customer and ten minor customers.

Application of KRA Reporting Standard:

If:	**Then:**
Example Company M asks its major customer to supply information about how Example PFAS M is processed and used, but that customer is unwilling to supply this information. Example Company M reasonably expects that the only remaining way to substantially fill this data gap would be to send a survey to its ten minor customers. Example Company M reports that the information is "not known or reasonably ascertainable" to it.	Duties Likely Fulfilled
Example Company M did not endeavor to obtain processing and use information from its customers and	Duties Not Fulfilled

designated the information as "not known or reasonably ascertainable."	

Scenario: Example Company N imports an article with a water repellant "fluoropolymer" surface. However, Example Company N does not know the chemical identity or molecular structure of the fluoropolymer coating.

Application of KRA Reporting Standard:

If:	Then:
Example Company N contacts their supplier to determine the name, CASRN, and molecular structure of the fluoropolymer. The supplier provides this information or a joint submission is initiated.	Duties Likely Fulfilled
Example Company N did not contact their supplier to obtain information on the fluoropolymer coating	Duties Not Fulfilled

Scenario: Example Company O imports stain-resistant garments. Example Company O does not know specifically what chemical is used to impart stain resistance, but Example Company O does know that chemicals used to impart stain resistance are often fluorinated chemicals and could meet the definition of PFAS.

Application of KRA Reporting Standard:

If:	Then:
Example Company O contacts their supplier to determine the name, CASRN, and molecular structure of the stain-resistant chemical. The supplier provides this information or a joint submission is initiated.	Duties Likely Fulfilled
Example Company O did not contact their supplier to obtain Duties Not Fulfilled information on the stain-resistant chemical.	Duties Not Fulfilled

4.3 Part I - Section A. Parent Company Information[4]

You must provide information about your parent company. For purposes of section 8(a)(7), a parent company is the highest-level company of your site's ownership hierarchy as of the start of the submission period according to the definitions of *parent company* and *highest-level parent company* at 40 CFR 711.3. Report your highest-level parent company located in the United States. Provide the company name, address, and D&B number following the instructions, including the naming conventions, provided below. Table 4-2 contains examples of how to identify the parent company in different situations.

Note that although CDR requires you to report your U.S. parent company and your foreign parent company, section 8(a)(7) reporting requires only the U.S. parent to be reported.

---

[4] See Section 4.4.1 for information concerning CBI claims for Parent Company Information.

Table 4-2. Applying Highest-level Parent Company Definition in Different Situations

Site Ownership	*U.S. Parent Company*
(1) If the site is entirely owned by a single U.S. company that is not owned by another company	Then that single company is the U.S. parent company.
(2) If the site is entirely owned by a single U.S. company that is, itself, owned by another U.S.-based company (e.g., it is a division or subsidiary of a higher- level company)	The highest-level domestic company in the ownership hierarchy is the U.S. parent company.
(3) If the site is owned by more than one company (e.g., company A owns 40 percent, company B owns 35 percent, and company C owns 25 percent of the site)	The company with the largest ownership interest in the site is the parent company. Under this scenario, this would be either company A itself (if it doesn't have a U.S.-based parent company), company A's parent, or, if it exists, a single parent company that owns both company B and company C, in which case that single parent company would have the largest ownership interest (e.g., corporation X owns companies B and C, for a total ownership of 60 percent for the site). If the parent company is a U.S. company owned by another U.S. company, then the highest-level domestic company in the ownership hierarchy is the U.S. parent company. If the parent company is a foreign company, then the site is its own U.S. parent company.
(4) If the site is ultimately owned by a 50:50 joint venture or a cooperative	The joint venture or cooperative is its own U.S. parent company.
	If the site is owned by a U.S. joint venture or cooperative, the highest level of the joint venture or cooperative is the U.S. parent company.
(5) If the site is entirely owned by a foreign company (i.e., without a U.S.-based subsidiary within the site's ownership hierarchy)	The site is the U.S. parent company.
(6) If the site is a federally owned site	The highest-level federal agency or department is the U.S. parent company.
(7) If the site is owned by a non-federal public entity	That entity (such as a municipality, State, or tribe) is the U.S. parent company.

4.3.1 U.S. Parent Company Name(s)

All sites must enter the full name of the U.S. parent company. EPA requires that parent companies be referenced consistently by the same name so that site-level information can be aggregated to the associated parent company. This can be challenging because filers within the same parent company often submit names with small variations (e.g., Exopack vs. Exopack Holdings Corp). When reporting your parent company name, eliminate all periods, commas, and all leading, trailing, and duplicate spaces. Replace commonly used acronyms and corporate terms according to Table 4-3.

Table 4-3. Parent Company Name Standardization

Use This	Not This
&	AND
CORP	CORPORATION
ASSOC	ASSOCIATION
CO	COMPANY
COS	COMPANIES
DIV	DIVISION
INC	INCORP
INC	INCORP.
INC	INCORPORATED
INC	INCORPERATED
LP	LIMITED PARTNERSHIP
LTD	LIMITED
LLC	LIMITED LIABILITY COMPANY
LLC	LIMITED LIABILITY CO.
PTNR	PARTNERSHIP
USA	U.S.A.
USA	U.S.A
USA	U S A
USA	UNITED STATES OF AMERICA
USA	UNITED STATES

4.3.2 Parent Company Dun & Bradstreet D-U-N-S® Number

Enter the 9-digit Dun & Bradstreet D-U-N-S® number (D&B number) associated with each parent company name. The number may be obtained from the treasurer or financial officer of the company.

D&B assigns separate numbers to subsidiaries and parent companies; you should make sure that the number you provide EPA belongs to your U.S. parent company. To verify the accuracy of your site and parent company D&B number and name, go to *www.dnb.com/product/dlw/form_cc4.htm* or call 1-800-234-3867. Callers to the toll-free phone number should understand that the D&B support representatives will need to verify that callers requesting the D&B number are an agent of the business. D&B recommends knowing basic information such as when the business originated, officer names, and the name, address, and phone number for the site.

For the purpose of responding to the section 8(a)(7) rule, you are ***not*** required to obtain a D&B number for your parent company if none exists. However, if your parent company does not have a D&B number, you can request one from your local office of D&B if desired. There is no charge for this service, and you are not required to disclose sensitive financial information to get a number. For more information on obtaining a D&B number, see *www.dnb.com*. If you are already listed with D&B, but do not know your number, you can call 1-800-234-3867 for assistance.

4.3.3 Parent Company Address

Enter the mailing address of each parent company, including the appropriate county or parish, using standard addressing techniques as established by the U.S. or international postal services. Post office box numbers should be accompanied by a street address. If a post office box is listed, it must be entered after the street address. Standardized conventions for listing a street address should be used to account for common formatting discrepancies, such as punctuation (by eliminating all periods, commas, and all leading, trailing, and duplicate spaces), capitalization, and abbreviations in order to increase the reliability and usability of the data. Replace commonly used acronyms and street abbreviations according to Table 4-4:

Table 4-4. Parent Company Street Address Standardization

Use This	Not This
AVE	AVENUE
AVE	AVE.
BLVD	BOULEVARD
BLVD	BLVD.
DR	DRIVE
DR	DR.
HWY	HIGHWAY
HWY	HWY.
JCT	JUNCTION
JCT	JCT.
LN	LANE
LN	LN.

PL	PLACE
PL	PL.
PO BOX	P.O. BOX
RD	ROAD
RD	RD.
RTE	ROUTE
ST	STREET
ST	ST.

4.4 Part I - Section B. Site Information

EPA requires the following information to be reported for each site at which a reportable chemical substance is manufactured: the site name, site D&B number, street address, city, county (or parish), state, and zip code, and six-digit North American Industry Classification System (NAICS) code(s) of the site.

4.4.1 Confidentiality of Company, Site, and Technical Contact Information

Check the appropriate CBI box in this block and complete the substantiation questions to assert a confidentiality claim for the link between the chemical substance and the company or site identity reported in Part I or the technical contact identity reported in Part II – Section B. Checking the CBI box automatically triggers the substantiation questions to appear later in the CBI Substantiation portion of the form. See Table 4-13Table 4-13 for substantiation questions related to these data elements. **If you do not check the CBI box for any information element, then that information is not claimed as CBI and may be made public without further notice to you.** Further, if you fail to substantiate your CBI claims in accordance with the statute and applicable rules, EPA may make the information available to the public without further notice to you. For additional information about how to answer substantiation questions, visit *www.epa.gov/tsca-cbi* on the EPA website.

You may assert a claim of confidentiality for a site, company, or technical contact identity to protect the link between that information and the reported chemical substance. Such claim may only be asserted where the linkage of that information to a reportable PFAS is confidential and not publicly available. You may claim the connection between chemical substance and company, site, or technical contact as confidential for some PFAS for which you are reporting, while not making the claim for others. Any confidentiality claims need to be made on a chemical-by-chemical basis. For example, if you claimed as confidential the link between chemical A and your company information and do not claim the link as confidential for chemical B, EPA may make the link between your company and chemical B public without notice. If the chemical identity is confidential, your company may instead claim the chemical identity as confidential to protect the link between the company, site, or technical contact information and the chemical identity. Ensure you are claiming the correct data elements as CBI to protect confidential data.

EPA also has observed that submitters sometimes claim only their company identity, but not their site identity, as confidential. EPA will not impute the existence of a CBI claim for site identity from a CBI claim for company identity, even if the company name appears within the site identity information. In other words, if your intent is to claim company name as confidential you must claim all data elements that reference or allude to company name as CBI. The failure to do this will likely result in a denial of a CBI claim for company name.

4.4.2 Special Provisions for Certain Sites

For PFAS that are domestically manufactured, the site is the location where the PFAS is physically manufactured.

For importers, the site where you import a chemical substance is considered the site of the operating unit within your organization that is directly responsible for importing the chemical substance and that controls the import transaction. For section 8(a)(7), all importers must provide a U.S. address for the controlling site; this site may be your company's headquarters in the United States. If there is no such operating unit or headquarters in the United States, the site address for the importer is the U.S. address of an agent acting on the importer's behalf who is authorized to accept service of process for the importer (40 CFR 711.3). In the event that more than one person may meet the definition of "importer" (40 CFR 704.3), only one person should report. See 40 CFR 711.22(b).

Example 4-1. The headquarters of your company is located in New Town. Your company owns a plant site located in Old Town, which is in a different state. A headquarters employee purchases and arranges to have 50,000 lb of Example PFAS P imported from Japan to the Old Town plant site. The headquarters site in New Town controls the import transaction and is the site reported.

Example 4-2. The headquarters of your company is located in New Town. Your company owns three manufacturing sites, Sites 1, 2, and 3, all located in different states. An employee based at headquarters purchases and arranges to have 50,000 lb of Example PFAS R imported from Japan. The chemical is distributed as follows: 2,000 lb is delivered to Site 1; 18,000 lb is delivered to Site 2; and 30,000 lb is delivered to Site 3. The headquarters in New Town controls the import transaction for all three sites, and therefore is responsible for reporting all 50,000 lb of Example PFAS R. The site reported is New Town.

4.4.3 Site Name

The section 8(a)(7) reporting tool will automatically populate the site name from the site used for CDX registration. If you need to change this information, you will need to make corrections or create a new site in CDX and create a new form for the corrected or new site.

4.4.4 Site Dun & Bradstreet Number D-U-N-S®

D&B assigns separate numbers to subsidiaries and parent companies; make sure that the number you provide EPA belongs to the individual site for which you are reporting. You are ***not*** required to obtain a D&B number for the site if none exists. However, if the site does not have a D&B number, you can request one from your local office of D&B if desired. Please refer to Section 4.3.2 for information on obtaining a D&B number.

4.4.5 Site Street Address

The reporting tool will automatically populate the site address from the site used for CDX registration. If you need to change this information, you will need to make corrections or create a new site in CDX and create a new form for the corrected or new site.

4.4.6 NAICS code

Enter the appropriate six-digit North American Industry Classification System (NAICS) code or choose the correct code for each site reported. The NAICS code is the standard used by Federal statistical agencies in classifying business establishments for the purpose of collecting, analyzing, and publishing statistical data related to the U.S. business economy. Information about NAICS codes can be obtained from the U.S. Census website at *www.census.gov/eos/www/naics/*.

In some circumstances it may be challenging to identify a single NAICS code for the site. In those circumstances, you may report up to three NAICS codes to more appropriately describe your site. For example, headquarters sites that import for other sites may have difficulty identifying a single NAICS code.

4.4.7 Technical Contact Information

This section requests information about the person whom EPA may contact for clarification of the information in your submission. The technical contact should be a person who can answer questions about the reported PFAS. Typically, a person located at the manufacturing site is best able to answer such questions. However, companies may use their discretion in selecting a technical contact or multiple technical contacts, as provided by the section 8(a)(7) online reporting tool. In selecting the technical contact, submitters should consider that EPA may have follow-up questions about a PFAS data submission years after the submission date. The technical contact need not be the person who signed the certification statement.

4.4.7.1 Technical Contact Name and Company Name

Enter the name of the person whom EPA may contact for clarification of information submitted. Enter the name of the company employing the technical contact. You may use the same technical contact for all chemicals submitted or you may use a different technical contact for each chemical.

4.4.7.2 Technical Contact Telephone Number and Email Address

Enter the technical contact's telephone number, including the area code, and the contact's email address. If the technical contact is outside of the United States, include the country code.

4.5 Part II - Section A. Chemical Substance Identification

You must use the Agency's Substance Registry Services (SRS) to report the chemical substance identification information consisting of the currently correct Chemical Abstracts (CA) Index Name and the correct corresponding Chemical Abstracts Service (CAS) Registry Number (CASRN), as described in Sections 4.5.4 and4.5.6. The SRS is EPA's central system for information about chemical substances that are tracked or regulated by EPA or other sources. It is the authoritative resource for basic information about chemicals, biological organisms, and other chemical substances of interest to EPA and its state and tribal partners.

The correct CA Index Name and CASRN must be reported separately for each reportable PFAS at your site. If you wish to report a PFAS listed on the confidential portion of the TSCA Inventory, you will need to report the PFAS using a TSCA Accession Number (the generic chemical name corresponding to the Accession Number will automatically be incorporated into your form). See Section 4.5.1 for details on how to report confidential chemical substances. If you have a low-volume exemption (LVE) case number for the chemical substance, that number may be used if a CASRN or Accession Number is not known to or reasonably ascertainable by you. If you know the CASRN or Accession Number for the chemical substance, report that number instead of an LVE case number.

You will be able to connect directly to the SRS database from the reporting tool to report the correct CA Index Names and CASRNs for all of your non-confidential chemical substances on the TSCA Inventory. TSCA Accession Numbers and generic chemical names will be listed instead of CA Index Names and CASRNs for chemical substances on the confidential portion of the TSCA Inventory. The use of the SRS to obtain the identities for all reportable chemical substances is a convenient way to meet the chemical nomenclature requirement and will help to prevent errors in the reporting of chemical identification information for section 8(a)(7).

Duplicative Reporting

The information in this section regarding physical form, described in Section 4.5.12, may have been previously reported under CDR. See Section 1.2 for instructions on how to inform EPA that this information has already been reported.

If certain information in section A is not known to or reasonably ascertainable by you (including your company), you may enter or select “NKRA” for “not known or reasonably ascertainable” in the box corresponding to that data element. You may only report NKRA in this section for the chemical ID, molecular structure, or physical state of the PFAS. You **may not** report NKRA for the specific or generic chemical name or trade or common name.

4.5.1 Confidentiality of Chemical Substance Information

If you wish to report a chemical substance listed on the confidential portion of the TSCA Inventory, you will need to report the chemical substance using a TSCA Accession Number.

Accession numbers are only assigned to inventory chemicals and not to other chemicals authorized to be in US commerce, like LVEs. The generic chemical name corresponding to the TSCA Accession Number will also be automatically incorporated into your report.

The identities of chemical substances listed on the public version of the TSCA Inventory are already publicly known. Therefore, claims for confidential treatment of the identity of a chemical substance which is listed on the public section of the TSCA Inventory are not valid and will not be allowed (40 CFR 715.30(a)(2)(i)). This includes claims for confidential treatment of the chemical name, ID, and molecular structure.

You may claim as confidential the identity (chemical name, CAS registry number, and molecular structure) of a chemical substance that is already listed as confidential on the TSCA Inventory (40 CFR 715.30(c)). To do so, you must check the appropriate CBI box and submit detailed written answers to the substantiation questions listed in Table 4-5. The confidentiality claim is only applicable to the information as it is listed on the confidential portion of the TSCA Inventory; the corresponding accession number and generic chemical name listed on the public portion of the TSCA Inventory is already public and cannot be claimed as confidential. You may also claim as confidential the identity of a chemical substance that is not listed on the TSCA Inventory, e.g., LVE substances. CBI claims for trade names or common names are allowed but may not be valid if the trade name or common name is public.

CBI claims for physical state(s) of the chemical are allowed regardless of the confidentiality status of the chemical. Substantiation questions to be answered for physical state CBI claims are the same questions to be answered for confidentiality of manufacturing information listed in Table 4-13Table 4-13 in Section 4.7.1.2

CBI claims for chemical identity will be accepted only when accompanied by a separate written substantiation for the chemical substances claimed as CBI, except for chemicals reported on article importer forms. Article importers are not required to assert CBI claims for chemical identity. Additionally, PFAS manufacturers (except article importers) who do not know nor can reasonably ascertain one of the following chemical-specific identifiers, are not required to assert and substantiate a CBI claim for the PFAS identity: CASRN, TSCA Accession number, or LVE number. Checking the CBI box automatically triggers the substantiation questions to appear later in the CBI Substantiation portion of the form. If you fail to click the checkbox next to “CBI for Chemical Identification" or fail to substantiate the claim for confidentiality of the chemical identity in accordance with applicable rules, EPA may make the information available to the public. Note that checking this box does not protect the link between your company and the chemical substance; it only asserts a CBI claim for the specific identity of the chemical substance as listed on the confidential portion of the TSCA Inventory.

Following the conclusion of the reporting period for this rule, EPA intends to compile a list of reported confidential Inventory substances for which either no chemical identity CBI claim was asserted or for which the claim was denied. Similar to past compilations, EPA will publish this list of candidates for disclosure on the public version of the Inventory, by TSCA accession number, on the EPA website for several months in advance of any update to the Inventory itself. Interested parties will have an opportunity to review the list for possible errors and contact EPA with any questions or concerns about specific candidates. In some cases, there may be assertions by a company that a mistake has been made (e.g., an incorrect chemical was reported), in which case EPA will undertake appropriate factual investigation as necessary to confirm whether there were any errors that would cause EPA to reconsider whether the chemical is no longer entitled to confidential Inventory protection. This investigation would take place prior to the point that the specific chemical identity would be disclosed on the public Inventory.

The requirements to report by Accession number, assert a CBI claim, and to substantiate such claims to maintain confidential Inventory treatment **do not apply** to submissions concerning imported articles. Such reporters may assert a CBI claim for trade name (if not already public) or other non-public identifiers, but need not report by Accession number or assert a CBI claim to maintain the confidential status of any chemical(s) associated with the trade name or generic chemical name. EPA will not determine the CBI status of a chemical identity based on imported article reporting.

Additional information about making and substantiating confidentiality claims is available on EPA's website, at *www.epa.gov/tsca-cbi*.

Table 4-5. Substantiation Questions to be Answered when Asserting Chemical Identity CBI Claims (40 CFR 705.30(e))

No.	Question
1.	Please specifically explain what harm to the competitive position of your business would be likely to result from the release of the information claimed as confidential. How would that harm be substantial? Why is the substantial harm to your competitive position likely (i.e., probable) to be caused by release of the information rather than just possible? If you claimed multiple types of information to be confidential (e.g., site information, exposure information, environmental release information, etc.), explain how disclosure of each type of information would be likely to cause substantial harm to the competitive position of your business.

No.	Question
2.	Has your business taken precautions to protect the confidentiality of the disclosed information? If yes, please explain and identify the specific measures, including but not limited to internal controls, that your business has taken to protect the information claimed as confidential. If the same or similar information was previously reported to EPA as non-confidential (such as in an earlier version of this submission), please explain the circumstances of that prior submission and reasons for believing the information is nonetheless still confidential.
3.	(i) Is any of the information claimed as confidential required to be publicly disclosed under any other Federal law? If yes, please explain. (ii) Does any of the information claimed as confidential otherwise appear in any public documents, including (but not limited to) safety data sheets; advertising or promotional material; professional or trade publications; state, local, or Federal agency files; or any other media or publications available to the general public? If yes, please explain why the information should be treated as confidential.
4.	Is the claim of confidentiality intended to last less than 10 years (see TSCA section 14(e)(1)(B))? If yes, please indicate the number of years (between 1–10 years) or the specific date after which the claim is withdrawn.
5.	Has EPA, another federal agency, or court made any confidentiality determination regarding information associated with this chemical substance? If yes, please provide the circumstances associated with the prior determination, whether the information was found to be entitled to confidential treatment, the entity that made the decision, and the date of the determination.
6.	Is this chemical substance publicly known (including by your competitors) to be in U.S. commerce? If yes, please explain why the specific chemical identity should still be afforded confidential status (*e.g.*, the chemical substance is publicly known only as being distributed in commerce for research and development purposes, but no other information about the current commercial distribution of the chemical substance in the United States is publicly available). If no, please complete the certification statement: I certify that on the date referenced, I searched the internet for the chemical substance identity (*i.e.*, by both chemical substance name and CASRN). I did not find a reference to this chemical substance that would indicate that the chemical is being manufactured or imported by anyone for a commercial purpose in the United States. [provide date].
7.	Does this particular chemical substance leave the site of manufacture (including import) in any form, *e.g.,* as a product, effluent, emission? If yes, please explain what measures have been taken to guard against the discovery of its identity.
8.	If the chemical substance leaves the site in a form that is available to the public or your competitors, can the chemical identity be readily discovered by analysis of the substance (*e.g.*, product, effluent, emission), in light of existing technologies and any costs, difficulties, or limitations associated with such technologies? Please explain why or why not.
9.	Would disclosure of the specific chemical name release confidential process information? If yes, please explain.

4.5.2 Are you manufacturing a mixture or a chemical substance of unknown or variable composition or a polymer?

You should report for PFAS that are chemical substances as defined by TSCA. Note that a mixture is not considered a chemical substance. ***Mixture*** *means any combination of two or more chemical substances if the combination does not occur in nature and is not, in whole or in part, the result of a chemical reaction; except that such term does include any combination which occurs, in whole or in part, as a result of a chemical reaction if none of the chemical substances comprising the combination is a new chemical substance and if the combination could have been manufactured for commercial purposes without a chemical reaction at the time the chemical substances comprising the combination were combined. (TSCA 3(10))*

If you manufacture a mixture, you must determine whether you manufactured any components of the mixture and report for each individual PFAS component of the mixture using the information known to or reasonably ascertainable by you.

If you manufacture a PFAS as a result of a chemical reaction, you may manufacture a chemical substance of unknown or variable composition (UVCB). A UVCB substance is an indefinite combination of chemicals, that does not meet the statutory definition of “mixture” at TSCA section 3(10), whose number and individual identities and/or composition are not precisely or completely known. A UVCB combination of chemicals is subject to reporting under section 8(a)(7) and is considered a single chemical substance.

- If you imported a mixture, you will need to report the individual PFAS components of the mixture.
- If you domestically manufactured a mixture, you will need to determine whether any PFAS chemical substances were formed from a chemical reaction that occurred as part of manufacturing the mixture. If a chemical reaction has occurred, a PFAS formed from the chemical reaction may be a chemical substance subject to reporting. If a chemical reaction has not occurred, you have not manufactured any reportable chemical substances in the production of the mixture. In such a case, the production of the mixture has not triggered any requirement to report under the PFAS data call.
- Domestic manufacturers and importers should also consider whether the combination of the chemicals they have domestically manufactured or imported (respectively) should be chemically identified for TSCA purposes as a single UVCB chemical substance instead of a mixture.

EPA has developed two Inventory nomenclature guidance documents related to the mixture-UVCB determination:

- Toxic Substances Control Act Inventory Representation for Chemical Substances of Unknown or Variable Composition, Complex Reaction Products and Biological Materials:

UVCB Substances. Available online at: www.epa.gov/sites/production/files/2015-05/documents/uvcb.pdf;

- Toxic Substances Control Act Inventory Representation for Combinations of Two or More Substances: Complex Reaction Products. Available online at: www.epa.gov/sites/production/files/2015-05/documents/rxnprods.pdf

Polymers are a specific type of chemical that may have unknown or variable composition. Polymers often consist of a mixture of molecules with varying degree of polymerization, so that individual polymer molecules have different chain lengths and/or branching and therefore have different molecular structures. For copolymers (polymers formed from multiple monomer species), there may also be variance in the ratio and connectivity of the monomer subunits. In that case, report the identity of each monomer and average ratios for each copolymer. A polymer should be reported as a single PFAS. Provide any known information about the structure and variability of the structure in the chemical description and molecular structure data fields.

4.5.3 How to Report when Chemical Identity is Unknown

In some cases, you may know that you are manufacturing (including importing) a PFAS but not know the identity of the PFAS. For instance, this can occur if you import a PFAS and your supplier will not disclose the identity of the chemical, or if you do not know the identity of reaction products or byproducts.

You must use all information known to or reasonably ascertainable by you to determine if you are manufacturing a PFAS. For example, if you import a type of product known to sometimes include PFAS, this could include reviewing purchase records, SDS or product data sheets, or contacting your supplier. Additionally, you may consider the generic or trade name provided by your supplier, published studies, results of testing or other analysis, or any other information known to or reasonably ascertainable by you, in determining whether you have a reportable PFAS. If you determine that the chemical substance is unlikely to be a PFAS as defined by section 8(a)(7), you are not required to report.

If you determine that the chemical substance likely meets the definition of PFAS, you must report the chemical even if you do not know its specific chemical identity. You must report a chemical ID number (i.e., CASRN, TSCA Accession number, or LVE number) if one is known to or reasonably ascertainable by you; note that CAS numbers, Accession numbers, and LVE numbers may be assigned to chemicals with unknown or variable composition. Additionally, if you know or can reasonably ascertain another entity who would be able to provide the chemical identity (e.g., a co-manufacturer or a foreign supplier), you must initiate a joint submission with that entity. See Section 4.13 for more details on joint submissions.

For the chemical name, report the CA Index name if known to or reasonably ascertainable by you. If the CA index name is not known to or reasonably ascertainable by you, provide the generic chemical name or description of the PFAS instead. If the PFAS is not on the public portion of the TSCA Inventory, you may claim the name as CBI. Substantiation is required unless the PFAS has not been introduced into commerce (TSCA section 14(c)(2)(G)).

Provide the trade name or common name as appropriate. If the PFAS does not have a trade name or common name, report "NA." For the molecular structure, provide a correct representative or partial chemical structure diagram, as complete as can be known, if one can be reasonably ascertained. Further details on what to include in the structure diagram are provided in Section 4.5.9.

4.5.4 Chemical Substance Identifying Number

Every chemical substance reported in accordance with the section 8(a)(7) rule must be accompanied by its correct CASRN, corresponding to the chemical substance's specific chemical name as described in Section 4.5.6. (40 CFR 705.15(b)(1)(i)). You may enter either a CASRN or the specific name of the chemical substance to select the appropriate CASRN/Chemical Abstracts (CA) Index Name combination from the SRS database.

Report the correct CASRN for your chemical substance if it is listed on the non-confidential portion of the TSCA Inventory. In the case of a chemical substance listed on the confidential portion of the TSCA Inventory, report the TSCA Accession Number as the chemical identifying number. Note that the SRS contains a cross-reference list that displays the Accession Number, generic chemical name, and PMN case number (or for an initial TSCA Inventory substance, the TSCA Inventory reporting form number) for any chemical substance listed on the confidential portion of the TSCA Inventory.

PFAS are often confidential and therefore are usually assigned Accession numbers. You can look up a chemical's Accession number in SRS if you have the PMN case number. You may also submit an inventory inquiry via the CDX TSCA communications module if your rights to access this information have been validated.

If the PFAS is not listed on the TSCA Inventory, it may have a low-volume exemption (LVE) case number. Report the LVE case number as the chemical identification number. If you also know the CASRN for the PFAS, report the CASRN instead. If none of these types of identification numbers have been assigned to the chemical, or if you do not know enough information about the chemical identity to determine one of those identification numbers, report NKRA.

4.5.5 ID Code

The code corresponding to the type of identifying number you selected in the SRS will be entered. See codes in Table 4-6.

Table 4-6. ID Code for Chemical Identifying Numbers

If the Number You are Reporting is a(n)	This Code Will be Entered
TSCA Accession Number	A
CAS Registry Number	C
Low-volume exemption (LVE) Case Number	L

4.5.6 Chemical Name

Report your chemical substance using the CA Index Name currently used to list the chemical substance on the TSCA Inventory. You can identify the CA Index name by searching SRS using a CASRN, the specific name of the chemical substance, or related synonyms. In the event that a synonym is used for multiple chemical substances, you should take care to select the correct substance. In describing the chemical substance, the EPA requires Chemical Abstracts Service (CAS) chemical nomenclature be used for identification purposes when it is available.

In cases where a chemical substance is listed on the confidential portion of the TSCA Inventory, the generic chemical name will automatically be incorporated into your report when you select the Accession Number.

In order to continue to protect the confidentiality of the underlying specific chemical identification information (i.e., the CASRN and specific chemical name as listed on the confidential portion of the Inventory), you must claim the chemical identity as confidential and complete the upfront substantiation. The Accession Number and generic chemical name will remain non-confidential. Failure to identify the chemical identity as confidential waives any confidentiality claim for the chemical identity and will likely result in the transfer of the chemical substance from the confidential portion of the TSCA Inventory to the public portion of the TSCA Inventory.

If any entity reports a PFAS by specific chemical identity and does not claim the specific chemical identity as CBI, EPA expects to determine that the specific chemical identity is no longer entitled to confidential treatment. However, EPA would not make this determination where an entity attests that it does not have knowledge of the specific chemical identity. Instead, an entity that does not have knowledge of a specific chemical identity must initiate a joint submission with its supplier or other manufacturer if that entity is known. In these cases, the secondary submitter would be responsible for providing the specific chemical identity and for asserting and substantiating any CBI claims concerning the specific chemical identity. See, e.g., 40 CFR 711.15(b)(3); 711.30(c). Importers of articles using the streamlined article import form are not required to assert or substantiate CBI claims for chemical identity. Therefore, joint submissions are not required or enabled for article importers.

4.5.7 Trade Name or Common Name

Report the common or trade name(s) by which the product is sold or commonly known.

4.5.8 Generic Chemical Name or Description

If you do not know the specific identity of the chemical substance, provide a description of the substance. If you claimed CBI for the chemical name, you must provide a generic chemical name. If the chemical is on the confidential portion of the TSCA Inventory, the generic chemical name will be pre-populated from EPA’s Substance Registry Service (SRS).

Generic chemical names must be sufficiently detailed to identify the reported chemical as a PFAS. Specifically, any generic chemical name reported for a PFAS that does not contain “fluor” in the name would be rejected by EPA as insufficient under TSCA section 14(c)(1)(C).

Additionally, any previously existing generic chemical names from earlier TSCA section 5 submissions for PFAS without “fluor” are insufficient. Further, even if a generic chemical name reported under the TSCA 8(a)(7) rule lacks the structural unit “fluor,” the Agency will identify the chemical substance as a PFAS.

4.5.9 Molecular Structure

Upload as an attachment a representative molecular structure. This is not required if your chemical is listed as a class I substance on the TSCA inventory. If the chemical has a single defined structure, provide a complete, correct chemical structure diagram. The diagram should clearly indicate the identity of the atoms and the nature of bonds joining the atoms. Any ionic charges or stereochemistry should be shown clearly. All known stereochemical details should be provided. Carbon atoms in ring systems and their attached hydrogen atoms need not be explicitly shown. Where applicable, specify the proportions of isomers or tautomeric forms, degree of neutralization, etc.

For a substance with unknown or variable composition, provide a correct representative or partial chemical structure diagram, as complete as can be known, if one can be reasonably ascertained. The diagram should indicate the characteristic structure or variable compositional elements of the substance. For PFAS described as reaction products, as much specific detail as possible should be provided.

For polymers, provide a simple, representative structural diagram that illustrates what you know or can reasonably ascertain concerning the key structural features of the polymer molecules. For example, you could identify the linkages formed during polymerization, the functional groups present, the range and typical values for the number of repeating structural units, and the relative molar ratios of the precursors. Indicate if the repeating substructures are arranged in a nonrandom order such as in graft or block arrangements. For example:

$HO\text{-}C(=O)\text{-}R\text{-}O\text{-}(C(=O)\text{-}R'\text{-}C\text{-}O\text{-}R\text{-}O)_n\text{-}H$

$3<n<10$, where R may be either

$-CF_2CF_2-$or $-CF_2CF-CF_3$

and R' may be either a 1,4-substituted benzene ring or -(CF2)-

4.5.10 Additional Information on Chemical Identity

In this free text field, provide any additional information known to or reasonably ascertainable by you regarding the identity, structure, or composition of the PFAS. This may include, but is not limited to, additional information on the composition of a UVCB chemical or descriptions of a polymer. Report any additional information that was known to or reasonably ascertainable by you at the time of the substance's manufacture. If no additional information is known to or reasonably ascertainable by you, leave this text field blank.

4.5.11 Special Provisions for Joint Submitters of Unknown Chemical Substances

You may report an alternate chemical name, and a trade name, in those instances where your supplier will not disclose to you the specific chemical name of an imported PFAS because the information is claimed confidential. In these cases, you and the supplier may report the information required in a joint submission, which is further discussed in Section 4.13 of this chapter. If you, as the importer, cannot provide the chemical name, supply a trade name or other designation to identify the proprietary chemical substance and provide the supplier's (secondary submitter's) company information. Complete as much of the section 8(a)(7) reporting as is known to or reasonably ascertainable by you. In addition, you must use the reporting tool to ask the supplier (secondary submitter) of the confidential chemical substance to directly provide EPA with the correct chemical identity (as described in Section4.5.2), in a joint submission with you. Note that if you actually know or can reasonably ascertain the specific chemical identity of the chemical, you must provide that information regardless of your supplier's confidentiality claims, rather than using a joint submission.

Your request to the supplier must include instructions for submitting chemical identity information electronically, using the reporting tool via CDX (see 40 CFR 711.35), and for clearly referencing your submission. Contact information for the supplier, a trade name or other designation for the chemical substance or mixture, and a copy of the request to the supplier must be included with your submission for the chemical substance. If your connection to your supplier's name and other contact information, including the trade name, is confidential, you must indicate so by checking the CBI box. Failing to check the CBI box may result in EPA making the information publicly available without further notice to you, the submitter.

Substantiation of this confidentiality claim is not required at the time of submission.

If the secondary submitter does not know the chemical components of a mixture supplied to you, they may ask their supplier to complete the form as a tertiary submitter. When the secondary (or tertiary, as appropriate) submitter responds to the primary submitter's request, the secondary submitter would use the reporting software to identify the chemical substance in question.

If this information is considered confidential, the secondary (or tertiary, as appropriate) submitter must indicate so by checking the CBI box and, in the case of the chemical identity as listed on the confidential portion of the TSCA Inventory, completing the required substantiation questions (as listed in section 4.5.1 of this document). The chemical-specific function cannot be claimed as confidential (see section 4.8 of this document for more information). Failing to check the CBI box may result in EPA making the information publicly available without further notice to the submitter.

These special provisions only apply in cases where the supplier will not reveal the pertinent chemical identity to you because it is claimed confidential. In the event that you actually know the chemical identity of a chemical substance subject to section 8(a)(7) reporting, you must provide that information irrespective of a supplier's confidentiality claims.

EPA will only accept joint submissions that are submitted electronically using the reporting tool via CDX (see 40 CFR 711.35) and that clearly reference the specific section 8(a)(7) submission to which they refer. See Section 4.13 in this chapter for more information on preparing joint submissions.

In the event that the supplier is unknown or no longer exists (e.g., supplier has gone out of business without a successor entity), provide as much identifying detail as is known to you and report NKRA for the secondary submitter. In this case a joint submission will not be required.

4.5.12 Physical Form

Report all physical forms of the PFAS at the time it is reacted or as it leaves your site (40 CFR 711.15(b)(2)). For each PFAS at each site, the submitter must report as many physical forms as applicable from the following six physical forms:

- Dry powder
- Pellets or large crystals
- Water- or solvent-wet solid
- Other solid
- Gas or vapor
- Liquid

4.6 Part II – Section B. The categories of use of each such substance or mixture

The processing or use information should be reported to the extent that it is known to or reasonably ascertainable by you (40 CFR 711.15). See Section 4.2 for a discussion of this reporting standard and examples of information that may or may not be known to or reasonably ascertainable by you.

If any information is not known or reasonably ascertainable by you (including your company), enter or select “NKRA” for “not known or reasonably ascertainable” in the box corresponding to that data element. Keep in mind that you **cannot** claim an “NKRA” designation as confidential.

4.6.1 Confidentiality of Processing and Use Information

Most data elements in Section B may not be claimed as confidential. You may not claim the following data elements as confidential:

- *Certain industrial processing and use data elements.* These data elements are a general description of how the chemical is used or processed and cannot be claimed as confidential:
  - type of process or use
  - industrial sector
  - function code

- *Certain Consumer and Commercial use data elements.* These data elements are a general description of how the chemical is used and cannot be claimed as confidential:
  - product category
  - function of the chemical in the consumer or commercial product
  - whether the chemical is used in commercial or consumer products
  - whether the chemical predictably is used in children’s products

In this section, you may only assert a claim of confidentiality for the maximum concentration of the chemical in any product. Checking the CBI box associated with this data element automatically triggers substantiation questions. **If you do not check the CBI box for any information element, then that information is not claimed as CBI and may be made public without further notice to you.** See Table 4-13Table 4-13 for substantiation questions to be answered when asserting CBI claims for processing and use information.

4.6.2 Industrial Processing and Use

For purposes of section 8(a)(7) reporting, an industrial use means use at a site at which one or more chemical substances or mixtures are manufactured (including imported) or processed (40 CFR 705.3).

For each PFAS manufactured (including imported), report up to ten unique combinations of the following data elements: the Type of Process or Use Operation (TPU) (described in Section 4.6.2.1), the Industrial Sector (IS) (described in Section4.6.2.2), and the Function Category (FC) (described in Section4.6.2.3) (40 CFR 705.15(c)(4)). A combination of these three data elements defines a potential exposure scenario for risk-screening and priority-setting purposes. If more than ten unique combinations apply to a chemical substance, you need only report the ten combinations for the chemical substance that cumulatively represent the largest percentage of production volume, measured by weight. The reporting tool will allow you to enter more than ten combinations if you choose to do so.

For each of these unique combinations, you are also required to report the percentage of production volume in Section C (described in Section 4.7.2.5), and information about worker exposure in Section F (described in Section4.10.5) (40 CFR 705.15(g)). When you reach these sections, the reporting tool will populate the TPU, IS, and FC codes reported in this section.

You are required to report information that is known to or reasonably ascertainable by you concerning the industrial uses of the PFAS manufactured (including imported) at sites you control and at sites controlled by people to whom you have either directly or indirectly (including through a broker/distributor, from a customer, etc.) distributed the reportable chemical substance (40 CFR 705.15(c)(1)).

4.6.2.1 Type of Process or Use Operation

To the extent that it is known to or reasonably ascertainable by you, report the code which corresponds to the appropriate Type of Processing or Use Operation (TPU) for the particular combination of IS and FC codes. Table 4-7 shows the codes and TPUs. Note that if a chemical substance is fully reacted (i.e., reporting "PC" for the processing code), then the chemical substance is wholly consumed and further processing and use information for that chemical substance will not exist. In such a situation, there is no further downstream processing and use information to be reported for that particular type of processing or use operation under 40 CFR 705.15(c)(1). A processing or use code may be reported more than once if more than one IS and/or FC code applies to the same processing or use operation. Definitions for each code are provided in Appendix D, which may assist you in determining which code to report.

Table 4-7. Codes for Reporting Types of Industrial Processing or Use Operations

Designation	Operation
PC	Processing as a reactant.
PF	Processing—incorporation into formulation, mixture, or reaction product.
PA	Processing—incorporation into article.
PK	Processing—repackaging.
U	Use—non-incorporative activities.

4.6.2.2 Industrial Sectors

Report the code that corresponds to the appropriate Industrial Sector (IS) for all sites that receive a reportable PFAS from you either directly or indirectly (including through a broker/distributor, from a customer of yours, etc.) and that process and use the PFAS to the extent that this information is known to or reasonably ascertainable by you (40 CFR

711.15(c)(2)). Table 4-8 shows the codes and sectors. Because an industrial sector may apply to more than one processing and use scenario for a chemical substance, the same IS code may be reported with different combinations of FC and TPU codes. A list identifying the correspondence between NAICS codes and IS codes is provided in Appendix D (Table D-2). Additional, more detailed information can be found on the CDR website at www.epa.gov/cdr. (The IS codes used for PFAS section 8(a)(7) reporting are the same as CDR IS codes).

When you chose the IS "Other," you also need to provide a written description of the use of the chemical substance. The written description should be used to provide a description at a comparable level of specificity as found with the current codes. It should not be used to add additional, more specific detail. Your description may include the NAICS code. If you select the IS "Other," a text box will appear for you to enter the description.

Table 4-8. Codes for Reporting Industrial Sectors

Code	Sector description
IS1	Agriculture, forestry, fishing, and hunting.
IS2	Oil and gas drilling, extraction, and support activities.
IS3	Mining (except oil and gas) and support activities.
IS4	Utilities.
IS5	Construction.
IS6	Food, beverage, and tobacco product manufacturing.
IS7	Textiles, apparel, and leather manufacturing.
IS8	Wood product manufacturing.
IS9	Paper manufacturing.
IS10	Printing and related support activities.
IS11	Petroleum refineries.
IS12	Asphalt paving, roofing, and coating materials manufacturing.
IS13	Petroleum lubricating oil and grease manufacturing.
IS14	All other petroleum and coal products manufacturing.
IS15	Petrochemical manufacturing.
IS16	Industrial gas manufacturing.
IS17	Synthetic dye and pigment manufacturing.
IS18	Carbon black manufacturing.
IS19	All other basic inorganic chemical manufacturing.
IS20	Cyclic crude and intermediate manufacturing.
IS21	All other basic organic chemical manufacturing.
IS22	Plastics material and resin manufacturing.
IS23	Synthetic rubber manufacturing.
IS24	Organic fiber manufacturing.
IS25	Pesticide, fertilizer, and other agricultural chemical manufacturing.
IS26	Pharmaceutical and medicine manufacturing.
IS27	Paint and coating manufacturing.
IS28	Adhesive manufacturing.

Code	Sector description
IS29	Soap, cleaning compound, and toilet preparation manufacturing.
IS30	Printing ink manufacturing.
IS31	Explosives manufacturing.
IS32	Custom compounding of purchased resins.
IS33	Photographic film, paper, plate, and chemical manufacturing.
IS34	All other chemical product and preparation manufacturing.
IS35	Plastics product manufacturing.
IS36	Rubber product manufacturing.
IS37	Non-metallic mineral product manufacturing (includes cement, clay, concrete, glass, gypsum, lime, and other non-metallic mineral product manufacturing)
IS38	Primary metal manufacturing.
IS39	Fabricated metal product manufacturing.
IS40	Machinery manufacturing.
IS41	Computer and electronic product manufacturing.
IS42	Electrical equipment, appliance, and component manufacturing.
IS43	Transportation equipment manufacturing.
IS44	Furniture and related product manufacturing.
IS45	Miscellaneous manufacturing.
IS46	Wholesale and retail trade.
IS47	Services.
IS48	Other (requires additional information).

4.6.2.3 Function Category

Report the code that corresponds to the appropriate Industrial Function Category (FC) for each particular combination of TPU and IS that you report (40 CFR 711.15(c)(3)). You must use the codes in Table 4-9 for reporting under this data call. These codes, based on Organisation for Economic Cooperation and Development (OECD) standards, were required for reporting of chemical substances designated by EPA as a high priority for risk evaluation for 2020 CDR reporting and were optional for the 2020 CDR for other chemical substances; if you reported to 2020 CDR, you may be familiar with these codes. If your site reported this PFAS to 2020 or earlier CDR using other codes, you will need to determine the appropriate 2020 CDR codes and report those in this section. Because data reported using other codes was not reported as required by the PFAS section 8(a)(7) rule, it is not considered duplicative. Descriptions for each FC and a crosswalk between the OECD-based 2020 CDR codes and 2016 CDR codes are provided in Appendix D (Table D-4Table D-4). This crosswalk may be helpful if you are already familiar with the 2016 CDR codes and can help you determine the correct 2020 CDR codes to use if you have previously reported the PFAS using 2016 CDR codes. Function Category codes to be used for section 8(a)(7) reporting are provided in Table 4-9.

If you select F999 (Other), you must provide a description of the function of the chemical substance. The written description should be used to provide a description at a comparable level of specificity as found with the current codes. It should not be used to add additional, more specific detail.

Function codes are based on the intended physical or chemical characteristic for when a chemical substance or mixture is consumed as a reactant; incorporated into a formulation, mixture, reaction product, or article; repackaged; or used (e.g., as an abrasive, a catalyst, or an elasticizer). However, the functional use categories for consumer or commercial categories cover the life cycle and describe the specific function that a chemical provides when used in the formulation of a product or article, or when used within an industrial process. While the function of a chemical may be the same across its life cycle, certain functions may only be appropriate for consideration in an industrial setting, while others may be relevant for a consumer or commercial setting. For more information on reporting consumer and commercial use data, see Section 4.6.3 below.

Table 4-9. Codes for Reporting Function Categories

Code	Category
F001	Abrasives
F002	Etching agent
F003	Adhesion/cohesion promoter
F004	Binder
F005	Flux agent
F006	Sealant (barrier)
F007	Absorbent
F008	Adsorbent
F009	Dehydrating agent (desiccant)
F010	Drier
F011	Humectant
F012	Soil amendments (fertilizers)
F013	Anti-adhesive/cohesive
F014	Dusting agent
F015	Bleaching agent
F016	Brightener
F017	Anti-scaling agent
F018	Corrosion inhibitor
F019	Dye
F020	Fixing agent (mordant)
F021	Hardener
F022	Filler
F023	Anti-static agent
F024	Softener and conditioner

Code	Category
F025	Swelling agent
F026	Tanning agents not otherwise specified
F027	Waterproofing agent
F028	Wrinkle resisting agent
F029	Flame retardant
F030	Fuel agents
F031	Fuel
F032	Heat transferring agent
F033	Hydraulic fluids
F034	Insulators
F035	Refrigerants
F036	Anti-freeze agent
F037	Intermediate
F038	Monomers
F039	Ion exchange agent
F040	Anti-slip agent
F041	Lubricating agent
F042	Deodorizer
F043	Fragrance
F044	Oxidizing agent
F045	Reducing agent
F046	Photosensitive agent
F047	Photosensitizers
F048	Semiconductor and photovoltaic agent
F049	UV stabilizer
F050	Opacifer
F051	Pigment
F052	Plasticizer
F053	Plating agent
F054	Catalyst
F055	Chain transfer agent
F056	Chemical reaction regulator
F057	Crystal growth modifiers (nucleating agents)
F058	Polymerization promoter
F059	Terminator/Blocker
F060	Processing aids, specific to petroleum production
F061	Antioxidant

Code	Category
F062	Chelating agent
F063	Defoamer
F064	pH regulating agent
F065	Processing aids not otherwise specified
F066	Energy Releasers (explosives, motive propellant)
F067	Foamant
F068	Propellants, non-motive (blowing agents)
F069	Cloud-point depressant
F070	Flocculating agent
F071	Flotation agent
F072	Solids separation (precipitating) agent, not otherwise specified
F073	Cleaning agent
F074	Diluent
F075	Solvent
F076	Surfactant (surface active agent)
F077	Emulsifier
F078	Thickening agent
F079	Viscosity modifiers
F080	Laboratory chemicals
F081	Dispersing agent
F082	Freeze-thaw additive
F083	Surface modifier
F084	Wetting agent (non-aqueous)
F085	Aerating and deaerating agents
F086	Explosion inhibitor
F087	Fire extinguishing agent
F088	Flavoring and nutrient
F089	Anti-redeposition agent
F090	Anti-stain agent
F091	Anti-streaking agent
F092	Conductive agent
F093	Incandescent agent
F094	Magnetic element
F095	Anti-condensation agent
F096	Coalescing agent
F097	Film former
F098	Demulsifier

Code	Category
F099	Stabilizing agent
F100	Alloys
F101	Density modifier
F102	Elasticizer
F103	Flow promoter
F104	Sizing agent
F105	Solubility enhancer
F106	Vapor pressure modifiers
F107	Embalming agent
F108	Heat stabilizer
F109	Preservative
F110	Anti-caking agent
F111	Deflocculant
F112	Dust suppressant
F113	Impregnation agent
F114	Leaching agent
F115	Tracer
F116	X-ray absorber
F999	Other

4.6.3 Consumer and Commercial Use

For purposes of section 8(a)(7) reporting, a commercial use means the use of a chemical substance or a mixture (including as part of an article) in a commercial enterprise providing saleable goods or a service (40 CFR 711.3). A consumer use, on the other hand, means the use of a chemical substance or a mixture (including as part of an article) when sold to or made available to consumers for their use (40 CFR 711.3).

For each PFAS manufactured (including imported), report up to ten unique combinations of the following data elements: the Product Category (PC) (described in Section4.6.3.1), the Function Category (FC) (described in Section4.6.3.2), whether the use is consumer and/or commercial (described in Section4.6.3.3), and whether the use is in products intended for use by children (described in Section4.6.3.4) (40 CFR 705.15(c)(7)). A combination of these four data elements defines a potential exposure scenario for risk-screening and priority-setting purposes. If more than ten unique combinations apply to a chemical substance, you need only report the ten combinations for the chemical substance that cumulatively represent the largest percentage of production volume, measured by weight (40 CFR 705.15(c)(4)). The reporting tool will allow you to enter more than ten combinations if you choose to do so.

For each of these unique combinations, you are also required to report the maximum concentration (described in Section4.6.3.5), the percentage of production volume (reported in Section C of the reporting form – described in Section4.7.2.6), and, for commercial uses, information about worker exposure (reported in section C of the reporting form – described in Section4.10.7) (40 CFR 711.15(c)(8)).

You are required to report information that is known to or reasonably ascertainable by you concerning the consumer and commercial end uses of each chemical substance manufactured (including imported) at sites you control and at sites controlled by people to whom you have either directly or indirectly (including through a broker/distributor, from a customer, etc.) distributed the reportable PFAS (40 CFR 711.15(c)(4)).

4.6.3.1 Product Category

You must designate up to ten product categories which correspond to the actual use of the chemical substance by reporting the codes which correspond to the appropriate product categories (40 CFR 711.15(c)(4)). If more than ten codes apply, you need report only the ten codes for the chemical substance that cumulatively represent the largest percentage of production volume, measured by weight (40 CFR 711.15(c)(4)). The reporting tool will allow you to enter more than ten categories if you choose to do so.

You must use the codes in Table 4-10Table 4-10 for reporting under this data call. These codes, based on OECD standards, were required for reporting of chemical substances designated by EPA as a high priority for risk evaluation for 2020 CDR reporting and were optional for the 2020 CDR for other chemical substances; if you reported to 2020 CDR, you may be familiar with these codes. If your site reported this PFAS to 2020 or earlier CDR using other codes, you will need to determine the appropriate 2020 CDR codes and report those in this section. Because data reported using other codes was not reported as required by the PFAS section 8(a)(7) rule, it is not considered duplicative. Descriptions for each product category code and a crosswalk between the OECD-based 2020 CDR codes and 2016 CDR codes are provided in Appendix D (Table D-3Table D-3).

This crosswalk may be helpful if you are already familiar with the 2016 CDR codes and can help you determine the correct 2020 CDR codes to use if you have previously reported the PFAS using 2016 CDR codes. Product Category codes are provided in Table 4-10.

If you select CC980 (Other), you must provide a description of the product category. The written description should be used to provide a description at a comparable level of specificity as found with the current codes. It should not be used to add additional, more specific detail.

Table 4-10. Product Category Codes

Code	Category
Chemical Substances in Furnishing, Cleaning, Treatment Care Products	
CC101	Construction and building materials covering large surface areas including stone, plaster, cement, glass and ceramic articles; fabrics, textiles, and apparel
CC102	Furniture & furnishings including plastic articles (soft); leather articles
CC103	Furniture & furnishings including stone, plaster, cement, glass and ceramic articles; metal articles; or rubber articles
CC104	Leather conditioner
CC105	Leather tanning, dye, finishing, impregnation and care products
CC106	Textile (fabric) dyes
CC107	Textile finishing and impregnating/surface treatment products
CC108	All-purpose foam spray cleaner
CC109	All-purpose liquid cleaner/polish
CC110	All-purpose liquid spray cleaner
CC111	All-purpose waxes and polishes
CC112	Appliance cleaners
CC113	Drain and toilet cleaners (liquid)
CC114	Powder cleaners (floors)
CC115	Powder cleaners (porcelain)
CC116	Dishwashing detergent (liquid/gel)
CC117	Dishwashing detergent (unit dose/granule)
CC118	Dishwashing detergent liquid (hand-wash)
CC119	Dry cleaning and associated products
CC120	Fabric enhancers
CC121	Laundry detergent (unit-dose/granule)
CC122	Laundry detergent (liquid)
CC123	Stain removers
CC124	Ion exchangers
CC125	Liquid water treatment products
CC126	Solid/Powder water treatment products
CC127	Liquid body soap
CC128	Liquid hand soap
CC129	Solid bar soap

Code	Category
CC130	Air fresheners for motor vehicles
CC131	Continuous action air fresheners
CC132	Instant action air fresheners
CC133	Anti-static spray
CC134	Apparel finishing, and impregnating/surface treatment products
CC135	Insect repellent treatment
CC136	Pre-market waxes, stains, and polishes applied to footwear
CC137	Post-market waxes, and polishes applied to footwear (shoe polish)
CC138	Waterproofing and water-resistant sprays
Chemical Substances in Construction, Paint, Electrical, and Metal Products	
CC201	Fillers and putties
CC202	Hot-melt adhesives
CC203	One-component caulks
CC204	Solder
CC205	Single-component glues and adhesives
CC206	Two-component caulks
CC207	Two-component glues and adhesives
CC208	Adhesive/Caulk removers
CC209	Aerosol spray paints
CC210	Lacquers, stains, varnishes and floor finishes
CC211	Paint strippers/removers
CC212	Powder coatings
CC213	Radiation curable coatings
CC214	Solvent-based paint
CC215	Thinners
CC216	Water-based paint
CC217	Construction and building materials covering large surface areas, including wood articles
CC218	Construction and building materials covering large surface areas, including paper articles; metal articles; stone, plaster, cement, glass and ceramic articles
CC219	Machinery, mechanical appliances, electrical/electronic articles
CC220	Other machinery, mechanical appliances, electronic/electronic articles
CC221	Construction and building materials covering large surface areas, including metal articles
CC222	Electrical batteries and accumulators

Code	Category
Chemical Substances in Packaging, Paper, Plastic, Toys, Hobby Products	
CC990	Non-TSCA use
CC301	Packaging (excluding food packaging), including paper articles
CC302	Other articles with routine direct contact during normal use, including paper articles
CC303	Packaging (excluding food packaging), including rubber articles; plastic articles (hard); plastic articles (soft)
CC304	Other articles with routine direct contact during normal use including rubber articles; plastic articles (hard)
CC305	Toys intended for children's use (and child dedicated articles), including fabrics, textiles, and apparel; or plastic articles (hard)
CC306	Adhesives applied at elevated temperatures
CC307	Cement/concrete
CC308	Crafting glue
CC309	Crafting paint (applied to body)
CC310	Crafting paint (applied to craft)
CC311	Fixatives and finishing spray coatings
CC312	Modelling clay
CC313	Correction fluid/tape
CC314	Inks in writing equipment (liquid)
CC315	Inks used for stamps
CC316	Toner/Printer cartridge
CC317	Liquid photographic processing solutions
Chemical Substances in Automotive, Fuel, Agriculture, Outdoor Use Products	
CC401	Exterior car washes and soaps
CC402	Exterior car waxes, polishes, and coatings
CC403	Interior car care
CC404	Touch up auto paint
CC405	Degreasers
CC406	Liquid lubricants and greases
CC407	Paste lubricants and greases
CC408	Spray lubricants and greases
CC409	Anti-freeze liquids
CC410	De-icing liquids
CC411	De-icing solids

Code	Category
CC412	Lock de-icers/releasers
CC413	Cooking and heating fuels
CC414	Fuel additives
CC415	Vehicular or appliance fuels
CC416	Explosive materials
CC417	Agricultural non-pesticidal products
CC418	Lawn and garden care products
Chemical Substances in Products not Described by Other Codes	
CC980	Other (specify)
CC990	Non-TSCA use

4.6.3.2 Functional Use for Consumer and/or Commercial Products

For each consumer and/or commercial product category reported, report the code(s) that designates the function category(ies) that best represents the specific manner in which the chemical substance is used (40 CFR 705.15(c)(5)). You must use the codes in Table 4-9Table 4-9 for reporting under this data call. These codes are the same as those used to report the appropriate Function Category for industrial processing and use. A particular function category may need to be reported more than once, to the extent that more than one consumer or commercial product category applies to a given function category.

For the special situation where the PFAS has multiple functions within the same product, you can report in one of two ways:

If one function is predominant, simply report the primary function; or

If all functions represent a substantial portion of the product, report each on a separate line and either estimate the portions individually or bifurcate the percent Production Volume (%PV) equally across the functions (so as not to double or triple-count the %PV for the one product).

If none of the listed function categories accurately describes a use of a chemical substance, the category "Other" may be used, and must include a description of the use. The written description should be used to provide a description at a comparable level of specificity as found with the current codes. It should not be used to add additional, more specific detail.

4.6.3.3 Consumer and/or Commercial Use

For each product category reported, report whether the use is a consumer use or a commercial use (40 CFR 705.15(c)(4). If the product has both consumer and commercial uses, report both.

4.6.3.4 Use in Product(s) Intended for Use by Children

Within each consumer product category reported, you must determine whether any amount of each reportable chemical substance manufactured (including imported) by you is present in or on any consumer product(s) intended for use by children age 14 or younger, regardless of the concentration of the chemical substance remaining in or on the product (40 CFR 705.15(c)(7)). If you determine that your chemical substance or mixture is used in a consumer product intended for use by children, report “Yes” in the “Used in Product(s) Intended for Children” column in Part II.D.2 of the reporting form. If you determine that your chemical substance or mixture is not used in a consumer product intended for use by children, report “No.”

EPA defines “intended for use by children” to mean the chemical substance or mixture is used in or on a product that is specifically intended for use by children age 14 or younger (40 CFR 705.3). Your chemical substance or mixture is intended for use by children if you answer “yes” to at least one of the following questions about the product into which your chemical substance or mixture is incorporated:

- Is the product commonly recognized (i.e., by a reasonable person) as being intended for use by children age 14 or younger?
- Does the manufacturer of the product state through product labeling or other written materials that the product is intended or will be used by children age 14 or younger?
    - Is the advertising, promotion, or marketing of the product aimed at children age 14 or younger?

Table 4-11Table 4-11 illustrates some (non-exhaustive) examples of “Use in Product(s) Intended for Use by Children.” For example, certain products (e.g., crayons, coloring books, diapers, and toy cars) are typically used by children age 14 or younger. If you determine that your chemical substance or mixture is used in crayons, for example, you would report “Y” for children’s use for CC305.

Certain products, such as household cleaning products, automotive supplies, and lubricants, typically are not intended to be used by children age 14 or younger. As such, if you determine that your chemical substance or mixture is used in automotive care products and lubricants, for example, you would report “no” for children’s use for categories CC401 and CC402.

Table 4-11. Examples of Products Intended for Use by Children

Code	Category	Examples
<u>Chemical Substances in Furnishings, Cleanings, Treatment Care Products</u>		
CC102	Furniture & furnishings including Plastic articles (soft); Leather articles	Child's car seat, children's sheets
CC103	Furniture & furnishings including Stone, plaster, cement, glass and ceramic articles; Metal articles; or Rubber articles	Baby cribs, changing tables
CC106	Textile (fabric) dyes	Children's clothing
CC107	Textile finishing and impregnating/surface treatment products	Children's clothing, children's sheets, child's car seat
CC127	Liquid body soap	Baby shampoo, children's bubble bath
<u>Chemical Substances in Construction, Paint, Electrical and Metal Products</u>		
CC219	Machinery, mechanical appliances, electrical/electronic articles	Electronic games, remote control cars
CC222	Electrical batteries and accumulators	Batteries used in toys
<u>Chemical Substances in Packaging, Paper, Plastic, Hobby Products</u>		
CC302	Other articles with routine direct contact during normal use, including paper articles	Diapers, baby wipes, coloring books
CC305	Toys intended for children's use (and child dedicated articles), including Fabrics, textiles, and apparel; or Plastic articles (hard)	Pacifiers, toy trucks, dolls, toy cars, wagons, action figures, balls, swing sets, slides, skates, baseball gloves, kid's rake
CC306	Adhesives applied at elevated temperatures	Craft glue for a hot glue gun
CC308	Crafting glue	Craft glue
CC309	Crafting Paint (applied to body)	Chemicals used to add color to body paint, finger paints

4.6.3.5 Maximum Concentration Code

When the chemical substance you manufacture (including import) is used in commercial or consumer products, you are required to report the estimated typical maximum concentration (measured by weight) of each chemical substance in each commercial or consumer product category reported (40 CFR 715.15(c)(8)). For each chemical substance used in a reported commercial or consumer product, report the code that corresponds to the appropriate concentration range. Table 4-12 shows the codes and concentration ranges.

Table 4-12. Codes for Reporting Maximum Concentration

Code	Concentration Range (weight percent)
M1	Less than 1% by weight
M2	At least 1 but less than 30% by weight
M3	At least 30 but less than 60% by weight
M4	At least 60 but less than 90% by weight
M5	At least 90% by weight

4.7 Part II – Section C. Manufacturing, Processing, and Use Information

The following subsections describe the manufacturing information required to be reported for each PFAS.

4.7.1 Confidentiality of Manufacturing Information

Information reported in the manufacturing section of the section 8(a)(7) form can be claimed as confidential. For most of the data elements, upfront substantiation of the claim is required. Specifically, upfront substantiation:

- IS NOT required for the annual domestically manufactured volume, imported volume.
- IS required for all other data elements.

Summary of substantiation requirements for claims of confidentiality:

All claims of confidentiality, except for information exempt from substantiation under TSCA section 14(c)(2) such as production volume information (including domestic manufacture and import), and certain information in joint submissions, must be substantiated at the time of submission as required by TSCA section 14(c)(3).

When using the reporting tool, you will be prompted to substantiate claims where CBI substantiations are required.

For additional information about how to answer substantiation questions, visit *www.epa.gov/tsca-cbi* on the EPA website.

For information on EPA's policy of reviewing CBI claims, visit *EPA Review and Determination of CBI Claims under TSCA* on the EPA website.

4.7.1.1 Confidentiality of Production Volume Information

Check the appropriate CBI box in this block to assert a confidentiality claim for the associated production volume information (domestically manufactured volume, imported volume, or percent production volume for each consumer and commercial use) being submitted. **If you do not check the CBI box for any information element, then that information is not claimed as CBI and may be made public without further notice to you.**

Further, if you fail to assert your CBI claims in accordance with the statute and applicable rules, EPA may make the information available to the public without further notice to you.

4.7.1.2 Confidentiality of all Other Manufacturing Information

Check the appropriate CBI box in this block and complete the substantiation questions to assert a confidentiality claim for the associated information being submitted. Checking the CBI box automatically triggers the substantiation questions to appear later in the CBI Substantiation portion of the form. See Table 4-13 for substantiation questions related to these data elements. **If you do not check the CBI box for any information element, then that information is not claimed as CBI and may be made public without further notice to you.** Further, if you fail to substantiate your CBI claims in accordance with the statute and applicable rules, EPA may make the information available to the public without further notice to you. For additional information about how to answer substantiation questions, visit *www.epa.gov/tsca-cbi* on the EPA website.

Table 4-13. Substantiation Questions to be Answered when Asserting Manufacturing, Processing, and Use-Related Confidentiality Claims (40 CFR 705.30(b))

No.	Question
1	Will disclosure of the information claimed as confidential likely cause substantial harm to your business's competitive position? If you answered yes, describe the substantial harmful effects that would likely result to your competitive position if the information is disclosed, including but not limited to how a competitor could use such information and the causal relationship between the disclosure and the harmful effects.
2	Has your business taken precautions to protect the confidentiality of the disclosed information? If yes, please explain and identify the specific measures, including but not limited to internal controls, that your business has taken to protect the information claimed as confidential.
3	i. Is any of the information claimed as confidential required to be publicly disclosed under any other Federal law? If yes, please explain. ii. Does any of the information claimed as confidential otherwise appear in any public documents, including (but not limited to) safety data sheets; advertising or promotional material; professional or trade publications; state, local, or Federal agency files; or any other media or publications available to the general public? If yes, please explain why the information should be treated as confidential. iii. Does any of the information claimed as confidential appear in one or more patents or patent applications? If yes, please provide the associated patent number or patent application number (or numbers) and explain why the information should be treated as confidential.
4	Does any of the information that you are claiming as confidential constitute a trade secret? If yes, please explain how the information you are claiming as confidential constitutes a trade secret.
5	Is the claim of confidentiality intended to last less than 10 years (see TSCA section 14(e)(1)(B))? If yes, please indicate the number of years (between 1–10 years) or the specific date after which the claim is withdrawn.
6	Has EPA, another federal agency, or court made any confidentiality determination regarding information associated with this chemical substance? If yes, please provide the circumstances associated with the prior determination, whether the information was found to be entitled to confidential treatment, the entity that made the decision, and the date of the determination.

4.7.2 Reporting Manufacturing Information

This section describes the manufacturing data elements that should be reported for your PFAS for each year. If any information is not known or reasonably ascertainable by you (including your company), enter or select “NKRA” for “not known or reasonably ascertainable” in the box corresponding to that data element. You may also check the CBI box next to each data element to claim data as confidential. However, keep in mind that you **cannot** claim an “NKRA” designation as confidential.

4.7.2.1 Domestically Manufactured Production Volume

Report the volume of the chemical substance domestically manufactured at your site, in pounds. Report the quantity to at least two significant figures; it should be accurate to the extent known to or reasonably ascertainable by you. Production volumes should be reported in numeric format, without commas (e.g., 6352000). See Table 4-14Table 4-14 for examples.

4.7.2.2 Imported Production Volume

Report the volume of the chemical substance imported by your site, in pounds. Report the quantity to at least two significant figures; it should be accurate to the extent known to or reasonably ascertainable by you. You should use the same numeric format as described for the domestically manufactured production volume. Imported and domestically manufactured production volumes are reported separately for each PFAS at each site.

Reporting for a chemical with multiple sources

If you import a PFAS from multiple sources, or domestically manufacture the PFAS through multiple processes, sum those sources together for reporting the total production volume, and consider the total amount for all other data fields.

If you import or domestically manufacture a chemical and also have quantities on site that were not manufactured by your site (e.g., purchased from a domestic source), consider **only the volume manufactured (including imported) by your site** when reporting total production volume and all other data fields. Do not report on quantities of the PFAS that were not manufactured (including imported) by your site.

Note that if you import various mixtures containing PFAS, you should add all import volumes associated with each PFAS. For

instance, if you import three mixtures and each mixture contains PFAS A, then you would determine the volume of PFAS A in each mixture and report the aggregated amount. See Table 4-14 for examples.

For article importers reporting on the Article Importer form, you should report the volume of the article imported, rather than attempting to calculate the volume of the PFAS contained within the articles. You may choose to report the total weight of the PFAS-containing articles (e.g., in tons or pounds) or the quantity of the article imported (e.g., the number of vehicles). You must specify the unit of measurement for the reported production volume.

4.7.2.3 For Imported Chemical Substances, Is the Chemical Never Physically at Site?

Report whether or not your imported PFAS is physically at the reporting site. Report one of the following choices:

☐ Yes, the imported PFAS **is never** physically at the reporting site (e.g., if you ship the chemical substance from a foreign country directly to another location such as a warehouse, a processing or use site, or a customer's site).

☐ No, the imported PFAS **is** physically present at the reporting site.

☐ NA, not applicable because the PFAS is not imported.

☐ NKRA, it is not known to or reasonably ascertainable by you whether the imported PFAS is physically present at the reporting site.

4.7.2.4 Volume Directly Exported

Report the volume directly exported and not domestically processed or used, in pounds. The volume exported should not exceed the sum of the domestically manufactured and imported volumes minus volume used on site. Note that direct exporting includes sending a PFAS to a distributor who then exports it without repackaging it, even if it is relabeled. Direct exporting does not include sending a PFAS to a distributor who repackages and relabels it. The latter case would be considered a processing and use activity potentially reportable under Part II – Section B of the reporting form. Report the quantity to at least two significant figures; it should be accurate to the extent known to or reasonably ascertainable by you. You should use the same numeric format as described for domestically manufactured production volume (see section4.7.2.1). See Table 4-14 for examples.

Table 4-14. Examples of Reporting Volumes for Part II – Section C

Description	Reporting Requirement
Example Site S domestically manufactures 31,415 lb of Example PFAS S.	Example Site S should report 31,415 lb as domestically manufactured for Example PFAS S. The total production volume (i.e., the domestically manufactured volume) should be used to report all remaining information.
Example Site T domestically manufactures 15,000 lb of Example PFAS T and directly imports 15,112 lb of Example PFAS T.	Example Site T should report 15,000 lb as domestically manufactured. Because Example Site T controls the import transaction, Example Site T should also report 15,112 lb as imported for Example PFAS T. The total production volume (i.e., sum of the domestically manufactured and import volumes, 30,112 lb) should be used to report all remaining information.

Description	Reporting Requirement
Example Site U domestically manufactures 33,500 lb of Example PFAS U. Of the 33,500 lb manufactured, Example Site U directly exports 13,000 lb to a foreign customer.	Example Site U should report 33,500 lb as domestically manufactured and 13,000 lb as exported for Example PFAS U. The volume not directly exported (20,500 lb) should be used to report all remaining information.
Example Company V coordinates the import of 105,000 lb of Example PFAS V, which is imported directly to three different sites owned by Company V. Site 1 receives 41,000 lb and Sites 2 and 3 each receive 32,000 lb of Example PFAS V.	Example Company V should report 105,000 lb as imported for Example PFAS V. The total production volume (i.e., the imported volume) should be used to report all remaining information. Because the three sites controlled by Company V did not control the import transaction, the sites are not required to report the imported volumes.
Example Site W domestically manufacturers 77,000 lb, imports 22,000 lb, and exports 11,000 lb of Example PFAS W.	Example Site W should report an amount that does not exceed 88,000 lb as volume used at site for Example PFAS W, as the volume used at site should not be greater than the sum of the domestically manufactured and imported volumes minus the volume exported (77,000 lb + 22,000 lb – 11,000 lb).
Example Site X imports 20,000 lb of Example PFAS X and purchases 30,000 lb of Example PFAS X from a domestic producer.	Example Site X should report 20,000 lb as imported for Example PFAS X. The total production volume is 20,000 lb; the 30,000 lb of Example PFAS X purchased from a domestic producer is not included because Example Site X is not the manufacturer of that quantity of PFAS X (i.e., Site X neither imported nor produced those 30,000 lb). Only the 20,000 lb of PFAS X imported should be considered throughout the entire section 8(a)(7) form.

4.7.2.5 Industrial Processing and Use – Percentage of Production Volume

Report the estimated percentage of total production volume of the PFAS associated with each unique combination of industrial processing or use operation, sector, and function category (TPU, IS, and FC) as reported in Part II – Section B of the reporting form (see section4.6.2). The percentage should be accurate to the extent that it is known to or reasonably ascertainable by you. Round your estimates to the nearest 10 percent of production volume (40 CFR 711.15(d)(4)). If you would like to provide more specific percentages, please do so. Do not round a particular combination that accounts for less than five percent of the total production volume to zero percent. In such cases, you must report the percentage of production volume attributable to that combination to the nearest one percent of production volume.

How to determine your percent production volume:

1. Determine the production volume that is attributable to each unique combination of TPU, IS, and FC.
2. Determine your total production volume for the year.
   a. Add together the volume domestically manufactured and the volume imported.
   b. DO NOT subtract the volume used on-site or the volume exported.
3. Divide the volume determined in step 1 by the volume determined in step 2 and multiply by 100.

The total percentage of production volumes associated with the TPU, IS, and FC combinations may add up to more than 100 percent, given that you are reporting on distribution of a PFAS to sites in your control as well as downstream sites, some of which are not immediate purchasers from your original manufacturing site. Thus, you may "double count" quantities of the PFAS as you consider its use at multiple sites. The sum may also add to more than 100% due to rounding.

Additionally, the total percentage of production volume may add up to less than 100 percent if, for example:

- You do not know or cannot reasonably ascertain information about how all of your production volume is processed or used;
- More than 10 combinations of codes are applicable to your chemical substance;
- You export a portion of the production volume;
- A portion of the production volume is used for commercial, or consumer uses rather than industrial uses; or
- Percentages round such that they do not sum to 100% (e.g., three use combinations that each account for one-third of total use will be reported as 30% each, totaling 90%).

Table 4-15 provides examples of reporting industrial processing and use data.

Table 4-15. Examples of Reporting Industrial Processing and Use Information

Description	Reporting Requirement
Example Site Y manufactures 12,000 lb of Example PFAS Y for processing for incorporation into a mixture. All of the production is for use in industrial sector IS17 (Synthetic Dye and Pigment Manufacturing). Of the production volume, 67% (8,000 lb) is used as an anti-stain agent and 33% (4,000 lb) is used as a viscosity modifier.	On line 3.A.1 of the Form, enter PF for type of process or use, IS17 for industrial sector, F090 for FC, and 70% for production volume. On line 3.A.2 of the form, enter PF for type of process or use, IS17 for industrial sector, F079 for FC, and 30% for production volume.
Example Site Z manufactures 50,000 lb of Example PFAS Z for processing for incorporation into a mixture. All of the production is for use under	On line 3.A.1 of the form, enter PF for type of process or use, IS17 for industrial sector, F090 for FC, and 100% for production volume. On line 3.A.2

Description	Reporting Requirement
industrial sector IS17 (Synthetic Dye and Pigment Manufacturing). Of the production volume, 97% (48,500 lb) is used as an anti-stain agent and 3% (1,500 lb) is used as a viscosity modifier.	of the form, enter PF for type of process or use, IS17 for industrial sector, and F079 for FC. Because less than 10% of the production volume is used as a viscosity modifier, enter the percentage to the nearest one percent, i.e., 3%, for production volume.

4.7.2.6 Consumer and Commercial Use – Percentage of Production Volume

Report the estimated percentage of total production volume of the reportable chemical substance associated with each consumer and commercial product category as reported in Part II – Section B of the reporting form (see Section 4-274.6.3.1). The percentage should be accurate to the extent that it is known to or reasonably ascertainable by you. Round your estimates to the nearest 10 percent of production volume (40 CFR 705.15(d)(5)). If you would like to provide more specific percentages, please do so. Do not round a particular combination that accounts for less than five percent of the total production volume to zero percent. In such cases, you must report the percentage of production volume attributable to that combination to the nearest one percent of production volume.

The total percentage of production volumes associated with the product codes may add up to more than 100 percent, given that you are reporting on distribution of a chemical substance to sites in your control as well as downstream sites, some of which are not immediate purchasers from your original manufacturing site. Thus, you may "double count" quantities of the PFAS as you consider its use at multiple sites. The sum may also add to more than 100% due to rounding.

How to determine your percent production volume:

1. Determine the production volume that is attributable to each consumer or commercial product category.
2. Determine your total production volume for the year.
   a. Add together the volume domestically manufactured and the volume imported.
   b. DO NOT subtract the volume used on-site or the volume exported.
3. Divide the volume determined in step 1 by the volume determined in step 2 and multiply by 100.

Additionally, the total percentage of production volume may add up to less than 100 percent if, for example:

- You do not know or cannot reasonably ascertain information about how all of your production volume is processed or used;
- More than 10 combinations of codes are applicable to your chemical substance;
- You export a portion of the production volume;
- A portion of the production volume is used for industrial uses rather than commercial/consumer uses; or

- Percentages round such that they do not sum to 100% (e.g., three use combinations that each account for one-third of total use will be reported as 30% each, totaling 90%).

Table 4-16 provides examples of reporting consumer and commercial use information.

Table 4-16. Examples of Reporting Consumer and Commercial Use Information

Description	Reporting Requirement
Example Site AB manufactures 12,000 lb of Example PFAS AB for processing for incorporation into a mixture. All of the production is for use in commercial products. Of the production volume, 67% (8,000 lb) is used in waterproofing sprays for apparel and 33% (4,000 lb) is used in paper packaging (for non-food use).	On one line, enter CC138 for PC and 70% for production volume. On another line, enter CC301 for PC and 30% for production volume.
Example Site CD manufactures 50,000 lb of Example PFAS CD for processing for incorporation into a mixture. All of the production is for use in commercial products. Of the production volume, 97% (48,500 lb) is used in waterproofing sprays for apparel and 3% (1,500 lb) is used in paper packaging (for non-food use).	On one line, enter CC138 for PC and 100% for production volume. On another line, enter CC301 for PC. Because less than 10% of the production volume is used in paper packaging, enter the percentage to the nearest one percent, i.e., 3%, for production volume.

4.7.2.7 Site-limited?

Indicate whether the PFAS was site-limited. Site-limited means a chemical substance is manufactured and processed only within a site and is not distributed as a chemical substance or as part of a mixture or article outside the site. Imported chemical substances are never site-limited. Report yes if the PFAS was site-limited, no if the PFAS was not site-limited, or NKRA if you do not know and cannot reasonably ascertain whether the PFAS was site-limited.

4.7.2.8 Recycled Volume

Report the volume of the manufactured PFAS, which otherwise would be disposed of as a waste, that is being removed from the waste stream (on site) and is being used for a commercial purpose (40 CFR 705.15(d)(7)). Report the quantity, in pounds, to at least two significant figures; it should be accurate to the extent known to or reasonably ascertainable by you. You should use the same numeric format as described for the domestically manufactured production volume.

Table 4-17 provides examples of reporting recycling activities.

Table 4-17. Examples of Reporting Recycling

Description	Reporting Requirement
Example Site EF manufactures 2,721 lb of Example PFAS EF, none of which is recycled instead of being disposed of as a waste.	Enter 0 as no portion of the chemical is being recycled.
Example Site GH manufactures 5,550 lb of Example PFAS GH, 1,650 lb of which is then recycled instead of being disposed of as a waste.	Enter 1,650 lb as the volume recycled.
Example Site IJ manufactures 52,000 lb of Example PFAS IJ, 10% (1,500 lb) of which is manufactured as a byproduct. That 1,500 lb is then directly recycled and the other 50,500 lb is sold into commerce.	Enter 1,500 lb as the volume recycled.
Example Site KL manufactures a chemical substance, WonderChem. The process to manufacture WonderChem results in the production of a byproduct, Example PFAS KL. Some portion of PFAS KL stays with WonderChem. The remaining portion of PFAS KL is 58,000 lb. Initially Site KL disposed of PFAS KL as a waste, but partway through the year discovered a use for PFAS KL and diverted the remaining portion (29,000 lb) from the waste stream. The full volume of WonderChem is intended for commercial use.	Enter the portion of Example PFAS KL that is being recycled instead of being disposed of as a waste. Do not include any quantity of PFAS KL that stays with and is distributed with WonderChem, because WonderChem is produced for commercial use and no quantity is intended to be disposed of as a waste or recycled. In this case, 29,000 pounds were recycled.
Example Site MN manufactures 12,000 lb of Example Chemical MN for processing by incorporation into a mixture. Of the production volume, 92% (11,040 lb) is processed for incorporation and 8% (960 lb) is shipped to a waste management facility that also recycles certain materials. The manufacturer cannot reasonably ascertain whether this portion of Example PFAS MN is being recycled or disposed of as a waste.	Enter NKRA as the manufacturer does not know and cannot reasonably ascertain whether PFAS MN is being recycled or disposed of as a waste.
Example Site OP manufactures 100% of Example PFAS OP (15,000 lb) as a byproduct. That 15,000 lb is then sold directly to a recycler.	Enter 15,000 lb as the entire volume of Example PFAS OP is known to be recycled rather than disposed of as a waste.

4.8 Part II – Section D. A description of the byproducts resulting from the manufacture, processing, use, or disposal of each such substance or mixture

In this section, report information about all byproducts resulting from the manufacture, processing, use, or disposal of the PFAS. Report information about all byproducts that are chemical substances, regardless of whether the byproducts are themselves PFAS. Information in this section is to be reported for each byproduct for each year. Report all information known to or reasonably ascertainable by you, including byproducts produced during processing, use, or disposal of the PFAS at sites not under your control.

Note that in the case that you produce a PFAS as a byproduct, you may also be required to report that PFAS on its own section 8(a)(7) form. For example, if you are reporting for PFAS A, and PFAS B is produced as a byproduct of manufacturing PFAS A, note that you may also need to complete a section 8(a)(7) form for PFAS B. In that case, you may indicate duplicative reporting for PFAS B in this section.

For purposes of section 8(a)(7) reporting, refer to the following definition of byproduct:

> ***Byproduct*** *means a chemical substance produced without separate commercial intent during the manufacture, processing, use, or disposal of another chemical substance(s) or mixture(s). (40 CFR 704.3)*

Manufacture for commercial purposes means:

(1) To manufacture, produce, or import with the purpose of obtaining an immediate or eventual commercial advantage, and includes, among other things, the “manufacture” of any amount of a chemical substance or mixture

  (i) for commercial distribution, including for test marketing, or

  (ii) for use by the manufacturer, including use for product research and development or as an intermediate.

(2) The term also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Byproducts and impurities without separate commercial value are nonetheless produced for the purpose of obtaining a commercial advantage, since they are part of the manufacture of a chemical substance for commercial purposes.

4.8.1 Confidentiality of Byproduct Information

Except for the byproduct source, any information reported in the byproducts section of the section 8(a)(7) form can be claimed as confidential. For all of the data elements in this section, upfront substantiation of the claim is required.

Check the appropriate CBI box in this block and complete the substantiation questions to assert a confidentiality claim for the associated information being submitted. Checking the CBI box automatically triggers the substantiation questions to appear later in the CBI Substantiation portion of the form. See Table 4-5 for substantiation questions related to the byproduct chemical identity and Table 4-13 for substantiation questions related to the other byproduct data elements. **If you do not check the CBI box for any information element, then that information is not claimed as CBI and may be made public without further notice to you**. Further, if you fail to substantiate your CBI claims in accordance with the statute and applicable rules, EPA may make the information available to the public without further notice to you. For additional information about how to answer substantiation questions, visit [*www.epa.gov/tsca-cbi*](http://www.epa.gov/tsca-cbi) on the EPA website.

4.8.2 Byproduct Name or Description

Report your chemical substance using the CA Index Name currently used to list the chemical substance on the TSCA Inventory. You can identify the CA Index name by searching SRS using a CASRN, the specific name of the chemical substance, or related acronyms. In the event that an acronym is used for multiple chemical substances, you should take care to select the correct substance. Using the search widget to select a substance will automatically populate both the chemical name and chemical ID.

If the name of the byproduct is unknown, describe the byproduct. The description may be a descriptive name, or you may describe the byproduct as specifically as possible. The description you provide should accurately and precisely convey as much information about the molecular structure of the byproduct as is known to you.

4.8.3 Byproduct Generic Chemical Name [if byproduct chemical name is CBI]

In cases where a chemical substance is listed on the confidential portion of the TSCA Inventory, the generic chemical name will automatically be incorporated into your report when you select the Accession Number.

4.8.4 Byproduct Chemical ID

Every byproduct reported in accordance with section 8(a)(7) requirements must be accompanied by its correct CASRN, corresponding to the chemical substance's specific chemical name as described in Section4.5.6. (40 CFR 705.15(e)(1)). You may use the search widget to enter either a CASRN or the specific name of the chemical substance to select the appropriate CASRN/Chemical Abstracts (CA) Index Name combination from the SRS database. Using the search widget to select a substance will automatically populate both the chemical name and chemical ID.

> Report the correct CASRN for your chemical substance if it is listed on the non- confidential portion of the TSCA Inventory. If your chemical substance is listed on the confidential portion of the TSCA Inventory, report the EPA-designated TSCA Accession Number.
>
> If your chemical substance is not on the TSCA Inventory, report the CASRN if one has been assigned. Report "NKRA" only if no CASRN has been assigned to the chemical substance or if the identity of the byproduct is not known to or reasonably ascertainable by you.

In the case of a chemical substance listed on the confidential portion of the TSCA Inventory, report the TSCA Accession Number as the chemical identifying number. Similarly, if a chemical substance has an LVE Number and a CBI claim, the reporter should report the LVE Number as the identifying number.

If the chemical substance is not listed on the TSCA Inventory, report the CASRN if one has been assigned to the chemical substance; report NKRA only if no CASRN, Accession Number, or LVE Number has been assigned or if you do not know and cannot reasonably ascertain the identity of the byproduct. If you do not know and cannot reasonably ascertain the identity of the byproduct, you must provide a generic, structural description of the byproduct.

4.8.5 Byproduct Source

Indicate whether the byproduct was created as a result of manufacturing, processing, use, and/or disposal. For example, a byproduct created unintentionally while manufacturing a PFAS was created as a result of manufacturing. A byproduct created during management of the PFAS waste, such as a combustion byproduct formed during thermal treatment, is considered to be created as a result of disposal.

4.8.6 Byproduct Release

Indicate whether the byproduct(s) were released to the environment. Select yes, no, or NKRA. For purposes of reporting under this section, “released to the environment” includes quantities of the chemical disposed of in contained land disposal units such as underground injection wells and landfills as well as releases directly to air, water, and soil.

4.8.7 Byproduct Release Medium

If the byproduct(s) were released to the environment, select all media to which the byproducts(s) were released: air, water, or land. If unknown, select NKRA. If the byproduct was not released, report “not applicable.”

4.8.8 Byproduct Release Volume

Report the total weight of the byproduct released to all media, in pounds. Report the quantity to at least two significant figures; it should be accurate to the extent known to or reasonably ascertainable by you. Release volumes should be reported in numeric format, without commas (e.g., 6352000). Report only the weight of the byproduct(s) released. Do not include the weight of other materials (e.g., water, solvents, containers, or other chemical substances).

If the byproduct was not released, report “not applicable.”

Table 4-18 provides some examples of facilities reporting byproduct information.

Table 4-18. Examples of Byproducts Reporting

Example	Reporting
Example Company QR manufactures Example PFAS QR and is completing the section 8(a)(7) form for Example PFAS QR. During treatment of PFAS QR-containing waste, the site produces 5.0 pounds of hydrogen fluoride. 80% of the hydrogen fluoride is captured by a dry scrubber and spent scrubber medium is disposed of on site in a landfill. The remaining 20% is directly released to air through the site's stacks.	Example Company QR enters CAS # 7664-39-3 as a byproduct. The section 8(a)(7) software populates the CAS name for the chemical, hydrofluoric acid. Company QR reports that the source of this byproduct was disposal. The company reports that the byproduct was released to air and land and 5.0 pounds were released.
Example Site ST manufactures Example PFAS ST and is completing a section 8(a)(7) form for Example PFAS ST. During manufacture of Example PFAS ST, another chemical substance is formed that is also a PFAS, Example PFAS UV. Most of PFAS UV remains in the company's product, but 12 pounds of PFAS UV are released to air on site.	Example Site ST enters the CAS number and CA name of Example PFAS UV and reports manufacturing as its source. Example Site ST reports that PFAS UV was released to air and that releases totaled 12 pounds. Example Site ST also completes a full section 8(a)(7) submission for Example PFAS UV, including reporting these releases in Section G of that reporting form.
Example Site WX manufactures Example PFAS WX. The company knows that during on-site processing of Example PFAS WX, a byproduct is formed, but the company does not know the identity of the byproduct. All of the byproduct produced remains in the company's product and is distributed into commerce.	Example Site WX reviews the information they know and can reasonably ascertain and determines that the specific chemical identity is unknown. Example Site WX provides a description of the byproduct and indicates "NKRA" for the Chemical ID. Example Site WX indicates that the byproduct was produced during processing and that the byproduct was not released to the environment. The site reports "N/A" for the byproduct release medium and release volume.
Example Site YZ manufactures Example PFAS YZ. During manufacture of Example PFAS YZ, two byproducts are formed, Example PFAS AA and Example PFAS BB. PFAS AA is separated from the mixture and all 150 pounds produced are disposed of in the site's on-site landfill. Most of PFAS BB remains in the product and is distributed into commerce. The company knows some amount of PFAS BB is released to air on site but cannot determine how much.	Example Site YZ first reports the chemical name and CAS number for PFAS AA and indicates that PFAS AA is produced during manufacturing. Site YZ reports that 150 lb of PFAS AA are disposed of to land. Next, Site YZ enters the name and CAS number of PFAS BB as another byproduct. For PFAS BB, the company reports its source as manufacturing and reports that it is released, to air, with total release quantity NKRA.

4.9 Part II – Section E. All existing information concerning the environmental and health effects of such substance or mixture

In this section, report all information concerning the environmental and health effects of the substance or mixture that is known to or reasonably ascertainable by you. This information includes but is not limited to:

- Toxicity information (e.g., in silico, in vitro, animal test results, human data); and
- Other data relevant to environmental and health effects including range-finding studies, preliminary studies, OSHA medical screening or surveillance standards reports, adverse effects reports.

4.9.1 Confidentiality of Environmental and Health Effects Information

Information reported in this section of the PFAS data reporting form can be claimed as confidential, but reporters should note that TSCA section 14(b) places significant limitations on confidentiality protections for information from health and safety studies. CBI claims for environmental and health effects are only valid if they would disclose certain information related to a company's process or operations used in the manufacturing of the chemical. For all of the data elements in this section, upfront substantiation of the claim is required. For any environmental or health effects information being claimed as CBI, you must also submit a sanitized version (omitting only information that is claimed as confidential and appropriately substantiated) of the study report or other attachment for public release.

Check the appropriate CBI box in this block and complete the substantiation questions to assert a confidentiality claim for the associated information being submitted. Checking the CBI box automatically triggers the substantiation questions to appear later in the CBI Substantiation portion of the form. See Table 4-5 for substantiation questions related to the byproduct chemical identity and Table 4-13 for substantiation questions related to other data elements. Further, **if you fail to substantiate your CBI claims *and to provide a sanitized version of the report or attachment* in accordance with the statute and applicable rules, EPA may make the information available to the public without further notice to you**. For additional information about how to answer substantiation questions, visit *www.epa.gov/tsca-cbi* on the EPA website. Redactions must be as sparing as possible. It is your responsibility to ensure that any sanitized reports are thoroughly sanitized. EPA may publicly release sanitized reports as provided by you. It is your responsibility to ensure you have fully sanitized the report and that any changes or redactions cannot be reversed in the submitted sanitized version.

4.9.2 OECD Harmonized Environmental and Health Effects Template (attachment)

Upload all known or reasonably ascertainable information concerning the environmental and health effects of the substance or mixture, using OECD Harmonized Templates (OHTs) if available for the endpoint being reported on. OHTs are available from the OECD website: *https://www.oecd.org/ehs/templates/harmonised-templates.htm*. This can be accomplished by using the freely available IUCLID6 software (*https://iuclid6.echa.europa.eu/*), exporting the dossier in the OHT working context, and uploading via this rule's reporting tool. As of this writing, EPA uses IUCLID6 v6.27.2; submitters using future IUCLID6 v7 can export their dossier via the "Export to previous major version" function described in the IUCLID Manual (*https://iuclid6.echa.europa.eu/documents/1387205/1809908/iuclid_functionalities_html_en.pdf/9d01cb53-902d-dbb6-fb00-fa141688c395?t=1667168830907*). Submitters using future versions IUCLID6 v8 and higher (such as IUCLID7) should consult with EPA before submitting their data to confirm the current data format acceptance standards. EPA can accept any dossiers generated using an earlier version of IUCLID6. You may already have data in this format if the company has submitted the studies under the European Union's Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation.

The reporting software will guide you through the process of uploading attachment(s).

4.9.3 Study Report (attachment)

Upload as attachment(s) any relevant study report(s). You are required to provide any test data on the health and environmental effects of the PFAS in your possession or control, and a description of any other health and environmental effects data on the substance known to or reasonably ascertainable by you. Data in the possession or control of either a parent company or an affiliated subsidiary located outside the U.S. are considered by the Agency to be data that should be known to or reasonably ascertainable by a submitter.

Data must be submitted in English. Standard literature citations may be submitted for data in the open scientific literature. Complete test data (not summaries) must be submitted if they do not appear in the open literature. Incomplete reports (e.g., from ongoing studies) are exempt from full reporting. However, you must describe the nature and objective of any incomplete study, report, or test, the name and address of any laboratory developing the data; progress to date; type of data collected; significant preliminary results; and an anticipated completion date. If significant preliminary results or final results are obtained prior to the submission deadline or any other additional information significant to the review of the notice becomes available to you, you must submit this information. This includes reports from studies not conducted by your company, such as studies commissioned by your company. The reporting software will guide you through the process of uploading attachment(s). You may consider developing and voluntarily submitting a robust study summary along with the record as EPA is interested in the potential utility of this information to reduce the future burden of reporting, but this may not be submitted in lieu of a full study report.

4.9.4 Supporting Information (attachment)

Upload as attachments any relevant supporting information. This section is intended for you to provide any supporting information related to the study reports uploaded in the previous section. Other data not related to the uploaded study reports will be uploaded in the "Other Data Relevant to Environmental or Health Effects" section (i.e., section 4.9.6 below). The reporting software will guide you through the process of uploading attachment(s).

4.9.5 Analytical/Test Methods

Use the text entry field to describe any and all known analytical or test methods for the PFAS substance. If the method is an EPA method or is substantially similar to an EPA method, you may state which EPA method is the basis of the test method used and clearly describe all modifications. If the method is not an EPA method or substantially similar to an EPA method, describe all steps of the method in as much detail as possible. Standard literature citations may be submitted for test methods described in the open scientific literature. Complete method descriptions (not summaries) must be submitted if they do not appear in the open literature.

4.9.6 Other Data Relevant to Environmental or Health Effects

Provide, as attachments, any other data relevant to environmental or health effects not published in a study report. Such information may include, but is not limited to, material safety data sheets (SDS), information on physical/chemical properties, preliminary studies, range-finding studies, OSHA medical screening or surveillance standards reports, adverse effects reports, anonymized or aggregated informal test results in workers, underlying environmental monitoring data, blood levels, or inhalation studies.

4.10 Part II – Section F. The number of individuals exposed, and reasonable estimates of the number who will be exposed, to such substance or mixture in their places of employment and the duration of such exposure

In this section, report information concerning workers' exposure to the PFAS. Reporting in this section includes information on the activities resulting in exposure, number of workers exposed and the maximum duration of exposure, at the manufacturing site as well as industrial users and commercial sites.

Information in this section may depend on knowledge of activities occurring at sites not under your control. Recall that information provided under section 8(a)(7) reporting follows the "known to or reasonably ascertainable" reporting standard, which may entail requesting information from downstream users. Refer to Section 4.2 of this Guidance Document for a discussion of the reporting standard.

4.10.1 Confidentiality of Worker Exposure Information

Information reported in the worker exposure section of section 8(a)(7) reporting can be claimed as confidential. For all of the data elements in this section, upfront substantiation of the claim is required.

Check the appropriate CBI box in this block and complete the substantiation questions to assert a confidentiality claim for the associated information being submitted. Checking the CBI box automatically triggers the substantiation questions to appear later in the CBI Substantiation portion of the form. See Table 4-13 for substantiation questions related to these data elements. **If you do not check the CBI box for any information element, then that information is not claimed as CBI and may be made public without further notice to you.** Further, if you fail to substantiate your CBI claims in accordance with the statute and applicable rules, EPA may make the information available to the public without further notice to you. For additional information about how to answer substantiation questions, visit *www.epa.gov/tsca-cbi* on the EPA website.

4.10.2 Worker Activity Descriptions

Describe the activities for workers at the manufacturing site. For example:

- Workers unload totes of the PFAS from delivery trucks into different containers in site chemical storage area.
- Workers take samples of the product for QA/QC testing.
- Workers clean reaction vessels which contain residual PFAS product and reactants.

4.10.3 Number of Workers Exposed at the Manufacturing Site

For each activity listed above, report the total number of workers reasonably likely to be exposed to the reportable PFAS at the manufacturing site (40 CFR 711.15(g)). Select the code corresponding to the appropriate range for the number of workers reasonably likely to be exposed to the PFAS during manufacture. Table 4-19 lists the codes and ranges.

Table 4-19. Codes for Reporting Number of Workers Reasonably Likely to be Exposed

Code	Range of Workers Reasonably Likely to be Exposed
W1	Fewer than 10 workers
W2	At least 10 but fewer than 25 workers
W3	At least 25 but fewer than 50 workers
W4	At least 50 but fewer than 100 workers
W5	At least 100 but fewer than 500 workers
W6	At least 500 but fewer than 1,000 workers
W7	At least 1,000 but fewer than 10,000 workers
W8	At least 10,000 workers

“Reasonably likely to be exposed” means “an exposure to a chemical substance which, under foreseeable conditions of manufacture, processing, distribution in commerce, or use of the chemical substance, is more likely to occur than not to occur. Such exposures would normally include, but would not be limited to, activities such as charging reactor vessels, drumming, bulk loading, cleaning equipment, maintenance operations, materials handling and transfers, and analytical operations. Covered exposures include exposures through any route of entry (inhalation, ingestion, skin contact, absorption, etc.), but excludes accidental or theoretical exposures” (40 CFR 711.3).

Persons reasonably likely to be exposed to a chemical substance include workers whose employment requires them to pass through areas where chemical substances are manufactured, processed, or used (e.g., production workers and foremen, process engineers, and plant managers). Workers employed to drive vehicles which transport the chemical substance should be included in the number of workers reasonably likely to be exposed to the chemical substance if they come into contact with the chemical substance during loading or unloading. For example, workers engaged in the connection or disengagement of hoses used to load or unload the chemical substance should be included. However, workers involved solely with transporting chemical substances in sealed containers that are totally enclosed with no potential for exposure should not be included.

In addition, when a site employs temporary, seasonal, or contract workers in the manufacture of a reportable chemical substance, these workers should be included in the number of workers reasonably likely to be exposed to a chemical substance if they work in areas where the chemical substance is manufactured. The term does not include those employees whose jobs are not associated with potential exposures to a chemical substance or mixture (e.g., administrative staff who never enter areas where the chemical substance is manufactured) and who are unlikely to be exposed to a chemical substance for even a brief period of time.

No allowance is made for personal protective equipment or for engineering controls that reduce but do not preclude exposure to a chemical substance; however, if contact between a worker and a chemical substance is highly improbable, the worker should not be included among those persons reasonably likely to be exposed to the chemical substance.

Workers are considered to be exposed even if the chemical does not enter the body. For instance, skin contact with a PFAS-containing article is considered an exposure if the worker comes into contact with the PFAS, even if it is believed not to migrate from the article or is not dermally absorbed.

There is no minimum duration or frequency of exposure for determining the number of workers reasonably likely to be exposed to a chemical substance. If it is determined that a worker is reasonably likely to be exposed at any time during the year for any length of time, this worker should be included in the estimate.

There is no minimum level of exposure to a PFAS below which a worker need not be counted among the number reasonably likely to be exposed to a chemical substance. Therefore, if a company knows that a chemical substance manufactured at the site is present in the air throughout the site, all workers at the site must be included in the number of workers reasonably likely to be exposed to the chemical substance.

When there is no potential exposure to a chemical substance, the code W1 corresponding to fewer than 10 workers would be reported. This would be the case, for instance, when a chemical substance is imported in sealed containers and resold without repackaging or is shipped from a foreign source directly to a customer.

Throughout this section, for clarity, the terms “exposed” and “exposure” are used to mean “reasonably likely to be exposed” and “reasonably likely exposure.”

4.10.4 Maximum Duration of Exposure for Manufacturing Workers

For each activity reported, indicate the maximum duration of exposure for any worker at the manufacturing site in hours per day and the maximum number of days per year that workers may be exposed. If workers have different lengths of exposure (for example, due to shift schedules or different job roles), consider two scenarios: the worker(s) who have the longest duration of exposure on any day of the year (called maximum daily exposure), and the worker(s) who are exposed on the highest number of days per year (called maximum annual exposure). For each of these workers, report the maximum duration of exposure on any single day as well as the number of days per year that the worker is reasonably likely to be exposed. For each activity, consider the following questions:

1) What worker or group of workers is exposed for the longest amount of time on any one day doing this activity?
    a. How long is that maximum amount of time that the worker or group of workers is exposed doing this activity?
    b. On how many days per year is this worker(s) exposed to the PFAS while doing this activity?
2) What worker or group of workers is exposed on the largest number of days each year doing this activity?
    c. How many days per year is that worker or group of workers exposed doing this activity?
    d. What is the longest amount of time that worker(s) is exposed doing this activity on any one day?

Report maximum daily exposure to the nearest hour, except for workers exposed for less than one hour. Report 1 hour for any worker exposed for less than one hour; do not round to zero. If you know the duration of exposure to a greater degree of precision than the nearest hour, report the more precise information. If work shifts at your site cross midnight, you may consider the work shift to be one day (e.g., a worker who is exposed on one shift from 10 PM until 6 AM the next day may be counted as one day of exposure and 8 hours of daily exposure). Recall that in this section, you are reporting exposure by activity. If a worker at your site may be exposed to the PFAS during multiple activities, report for each activity considering that activity alone, and not any other activities.

Table 4-20 shows how companies would report in various example scenarios.

Table 4-20. Example manufacturing worker exposure scenarios

Exposure Scenario	Exposure for worker(s) with maximum daily exposure	Exposure for worker(s) with maximum annual exposure
Example Site CC has reported reaction vessel clean-outs as an activity with worker exposure to Example PFAS CC. Production line workers perform one thorough clean out per year, which takes 10 hours, and less-thorough monthly clean-outs, which each take 5 hours, for a total of 12 cleanings per year. The same workers perform all cleanouts.	Report 10 hours as the maximum daily exposure, because this is the longest duration of exposure for workers on any single day. Report 12 days as the maximum annual frequency, because these workers are exposed up to 12 days per year.	In this case, this activity is only done by one group of workers, so the workers with the maximum daily exposure are also the workers with the maximum annual exposure. Report 10 hours as the maximum daily exposure and 12 days as the maximum annual frequency.
At Example Site DD, workers may be exposed to Example PFAS DD when charging reactor vessels, a process that usually takes one hour but sometimes takes up to two hours. Reactor vessels are charged every day and the site operates 360 days per year, but no one worker works more than 5 days per week, or 260 days per year.	Report 2 hours as the maximum daily exposure, because this is the longest amount of time the activity takes. Report 260 days per year as the maximum annual exposure, because any single exposed worker may be exposed up to 260 days per year.	In this case, this activity is only done by one group of workers, so the workers with the maximum daily exposure are also the workers with the maximum annual exposure. Report 2 hours as the maximum daily exposure and 260 days as the maximum annual frequency.
Example Site EE imports Example PFAS EE in sealed vessels, re-labels the containers, and ships the containers without repackaging. No workers are expected to be exposed to PFAS EE.	Because no activities resulting in worker exposure occurred, report "N/A" for this section.	Because no activities resulting in worker exposure occurred, report "N/A" for this section.
Workers at Example Site FF are reasonably expected to be exposed to Example PFAS FF while charging reactor vessels, which takes no more than 3 hours. Reactor vessels are charged every day. The site rotates staff duties, so that no worker performs reactor vessel charging more than one day per week, or 52 times per year. Line supervisors may also be briefly exposed to PFAS FF during this activity. Supervisory duties are split equally between two workers, so that each performs this duty 180 days per year.	The workers with the maximum daily exposure for this activity are the workers actually charging reaction vessels, who may be exposed for up to 3 hours in a single day. Report 3 hours for the maximum daily exposure in this section. These workers are exposed up to 52 days per year, so report 52 days as the maximum annual exposure in this section.	The workers with the maximum annual exposure for this activity are the supervisors, who may each be exposed for up to 180 days during the year. These workers are exposed for no more than 15 minutes on any given day. Report 1 hour (do not round exposures less than one half-hour down to zero) for the maximum daily exposure and 180 days as the maximum annual exposure in this section.

Exposure Scenario	Exposure for worker(s) with maximum daily exposure	Exposure for worker(s) with maximum annual exposure
Workers at Example Site GG are exposed to Example PFAS GG during two activities: transferring the chemical from totes to smaller vessels and cleaning empty totes. Workers transfer the chemical from totes multiple times per day, resulting in total daily exposure of up to one hour. Workers perform this activity at the site up to 208 days per year. Empty totes are cleaned twice a year and the process takes two hours. The same workers do both tasks.	Transfer to smaller vessels: Workers are exposed to PFAS GG for a maximum of 1 hour per day while transferring the chemical. This exposure may happen on a maximum of 208 days per year. Report 1 hour per day and 208 days per year for this activity. Tote cleaning: Workers are exposed to PFAS GG for up to two hours while cleaning totes, which may occur a maximum of two days per year. Report 2 hours and 2 days per year for this activity.	In this case, the workers with the maximum daily exposure and maximum annual exposure are the same for each activity. Report 1 hour per day and 208 days per year for chemical transfer and 2 hours and 2 days per year for tote cleaning. Note that although the same workers perform both activities, reporting in this section is by activity. Do not combine exposure from multiple activities when reporting in this section.

4.10.5 Number of Workers Exposed for each Industrial Process and Use

For each unique combination of Type of Process or Use Operation, Industrial Sector, and Function Category, estimate the total number of workers that are reasonably likely to be exposed to the chemical substance at sites that process or use the chemical substance (40 CFR 711.15(g)(4)). Include workers at sites that are not under your control as well as those sites you control. For each combination of TPU, sector, and function, report the code that corresponds to the estimated range of the number of workers reasonably likely to be exposed. Table 4-19 shows the codes and worker ranges. See Section 4.10.3 for a discussion of “reasonably likely to be exposed.”

4.10.6 Maximum Duration of Exposure for Industrial Workers

For each unique combination of Type of Process or Use Operation, Industrial Sector, and Function Category, estimate the maximum duration of exposure for workers that are reasonably likely to be exposed to the chemical substance at sites that process or use the chemical substance. Include workers at sites that are not under your control as well as those sites you control.

If workers have different lengths of exposure (for example, due to shift schedules or different job roles), consider two scenarios: the worker(s) who have the longest duration of exposure on any day of the year (called maximum daily exposure), and the worker(s) who are exposed on the highest number of days per year (called maximum annual exposure). For each of these workers, report the maximum duration of exposure on any single day as well as the number of days per year that the worker is reasonably likely to be exposed. For each activity, consider the following questions:

1. What worker or group of workers is exposed for the longest amount of time on any one day for this combination of Type of Process or Use Operation, Industrial Sector, and Function Category?
    a. How long is that maximum amount of time that the worker or group of workers is exposed for this TPU/IS/FC combination?
    b. On how many days per year is this worker(s) exposed to the PFAS for this TPU/IS/FC combination?

2. What worker or group of workers is exposed on the largest number of days each year doing this activity?
    a. How many days per year is that worker or group of workers exposed for this TPU/IS/FC combination?
    b. What is the longest amount of time that worker(s) is exposed for this TPU/IS/FC combination?

Report maximum daily exposure to the nearest hour, except for workers exposed for less than one hour. Report one hour for any worker exposed for less than one hour; do not round to zero. If work shifts cross midnight, you may consider the work shift to be one day (e.g., a worker who is exposed on one shift from 10 PM until 6 AM the next day may be counted as one day of exposure and 8 hours of daily exposure). Recall that in this section, you are reporting exposure by activity. If a worker at your site may be exposed to the PFAS during multiple activities, report for each activity considering that activity alone, and not any other activities.

Table 4-21. Example industrial worker exposure scenarios

Exposure Scenario	Exposure for worker(s) with maximum daily exposure	Exposure for worker(s) with maximum annual exposure
Example Site HH incorporates Example PFAS HH into a metalworking fluid. Site HH knows that workers at its customers' facilities may work with the metalworking fluid for an entire shift and are reasonably likely to be exposed to the PFAS during this activity, which may occur on a daily basis. Site HH also knows its customers operate on 4x10-hour shift schedule, and therefore exposed workers are likely to be exposed for up to 10 hours per day, up to 4 days per week, or 208 days per year.	Report 10 hours per day as the maximum duration per day for this this combination of Type of Process or Use Operation, Industrial Sector, and Function Category. Report 208 days per year as the maximum duration per year.	In this case, this activity is only done by one group of workers, so the workers with the maximum daily exposure are also the workers with the maximum annual exposure. Report 10 hours as the maximum daily exposure and 208 days as the maximum annual frequency.

Exposure Scenario	Exposure for worker(s) with maximum daily exposure	Exposure for worker(s) with maximum annual exposure
Example Site II manufactures Example PFAS II and processes the chemical on site. The site knows that its processing activity is reasonably expected to expose workers for no more than 3 hours per day and occurs on Monday and Thursday every week. One group of production workers performs the activity on Mondays and a different group of workers performs the activity on Thursdays. One supervisor may also be exposed for no more than one hour during the activity. The same supervisor oversees the activity every time it is performed.	The workers with the most exposure on any given day are the production workers, who are exposed for up to 3 hours per day. Report 3 hours per day for the workers with the maximum daily exposure for this combination of TPU, IS, and FC codes. Report 52 days as the maximum duration per year for workers with the maximum daily exposure for this this combination of TPU, IS, and FC codes, because no single production worker is exposed more than one day per week, or 52 days per year.	The worker with the largest number of days of exposure is the supervisor, who may be exposed twice per week, or 104 days per year. The supervisor is not exposed for more than one hour per day during this activity, so report 1 hour for the maximum daily exposure for the worker with maximum annual exposure. Report 104 days per year for the maximum annual frequency of exposure for the worker with the maximum daily exposure.
Example Site JJ imports a PFAS chemical in an article. The PFAS chemical is part of a non-stick coating on the inside of equipment and workers are not expected to have physical contact with the internal non- stick surface.	Report N/A for this combination of TPU, IS, and FC codes.	Report N/A for this combination of TPU, IS, and FC codes.

4.10.7 Number of Workers Exposed for each Commercial Use

Report the total number of commercial workers, including those at sites not under your control that are reasonably likely to be exposed while using the reportable chemical substance, with respect to each commercial use (40 CFR 705.15(g)(5)). For each combination of commercial Product Category and Function Category reported (Section4.6), report the code which corresponds to the appropriate range of commercial workers reasonably likely to be exposed. Table 4-19 shows the codes for numbers of workers. See Section 4.10.3 for a discussion of “reasonably likely to be exposed.”

4.10.8 Maximum Duration of Exposure for Commercial Workers

For each unique combination of Product Category and Function Category, estimate the maximum duration of exposure for workers that are reasonably likely to be exposed to the chemical substance at sites that process or use the chemical substance. Include workers at sites that are not under your control as well as those sites you control.

If workers have different lengths of exposure (for example, due to shift schedules or different job roles), consider two scenarios: the worker(s) who have the longest duration of exposure on any day of the year (called maximum daily exposure), and the worker(s) who are exposed on the highest number of days per year (called maximum annual exposure). For each of these workers, report the maximum duration of exposure on any single day as well as the number of days per year that the worker is reasonably likely to be exposed. For each activity, consider the following questions:

1. What worker or group of workers is exposed for the longest amount of time on any one day for this combination of Product Category and Function Category?
    a. How long is that maximum amount of time that the worker or group of workers is exposed for this PC/FC combination?
    b. On how many days per year is this worker(s) exposed to the PFAS for this PC/FC combination?
2. What worker or group of workers is exposed on the largest number of days each year doing this activity?
    a. How many days per year is that worker or group of workers exposed for this PC/FC combination?
    b. What is the longest amount of time that worker(s) is exposed for this PC/FC combination?

Report maximum daily exposure to the nearest hour, except for workers exposed for less than one hour. Report one hour for any worker exposed for less than one hour; do not round to zero. If work shifts cross midnight, you may consider the work shift to be one day (e.g., a worker who is exposed on one shift from 10 PM until 6 AM the next day may be counted as one day of exposure and 8 hours of daily exposure). Recall that in this section, you are reporting exposure by activity. If a worker may be exposed to the PFAS during multiple activities, report for each activity considering that activity alone, and not any other activities.

Table 4-22. Example commercial worker exposure scenarios

Exposure Scenario	Exposure for worker(s) with maximum daily exposure	Exposure for worker(s) with maximum annual exposure
Example Company KK incorporates Example PFAS KK into a lubricating wax. Many of its customers are sporting good rental and repair shops, including ski shops and bike shops. Company KK knows that workers are likely exposed to the PFAS when applying lubricating waxes to equipment, an activity that may be done intermittently throughout a shift. Company KK knows from discussions with its customers that ski shops use the wax daily during the ski season, and that workers work up to 12 hour shifts up to 5 days per week during this 20-week season; the shops are closed the rest of the year. Bike shops using these products operate with shifts no longer than 10 hours long, up to 5 days per week year round.	The ski shop workers in this scenario have the longest maximum exposure on any given day and should be considered the workers with the maximum daily exposure. The ski shop workers work up to 12 hours at a time. Although exposure is intermittent, these workers may be exposed throughout the 12 hour shift. Company KK reports 12 hours as the maximum daily exposure. The ski shop workers work up to 100 days per year, so Company KK reports 100 days per year as the maximum annual exposure for the workers with the maximum daily exposure.	The bike shop workers in this scenario are exposed for the most days per year and should be considered the workers with the maximum annual exposure. Bike shop workers work up to 10 hours at a time. Although exposure is intermittent, these workers may be exposed throughout the 10 hour shift. Company KK reports 10 hours as the maximum daily exposure for the workers with maximum annual exposure. The bike shop workers work up to 260 days per year, so Company KK reports 260 days per year as the maximum annual exposure.
Example Company LL uses PFAS LL as a stain-resistant coating for carpets sold to commercial customers. Company LL knows from news reports that PFAS from coated carpets can be released into indoor air and dust over time, resulting in worker exposure. Company LL assumes that its commercial customers operate with 8 hours shifts and that workers work five days per week, 52 weeks per year.	Example Company LL estimates that workers in commercial customers using its carpets are exposed for eight hours per day, five days per week. Example Company LL reports 8 hours as the maximum daily exposure and 260 days as the maximum annual exposure for workers with the maximum daily exposure.	In this case, this Product Category/Function Category for Example PFAS LL is only done by one group of workers, so the workers with the maximum daily exposure are also the workers with the maximum annual exposure. Company LL reports 8 hours as the maximum daily exposure and 260 days as the maximum annual exposure for workers with the maximum annual exposure.
Example Site MM produces a PFAS-coated part used in commercial machines. The PFAS is not expected to produce any emissions or migrate from the coating under normal conditions of use.	Site MM reports 0 hours per day and 0 days per year, as workers are not expected to be exposed for any amount of time.	Site MM reports 0 hours per day and 0 days per year, as workers are not expected to be exposed for any amount of time.

4.11 Part II – Section G. The manner or method of its disposal, and in any subsequent report on such substance or mixture, any change in such manner or method

4.11.1 Confidentiality of Disposal Information

Information reported in the disposal section of the section 8(a)(7) reporting form can be claimed as confidential if it is not already public information. For all of the data elements in this section, upfront substantiation of the claim is required.

Check the appropriate CBI box in this block and complete the substantiation questions to assert a confidentiality claim for the associated information being submitted. Checking the CBI box automatically triggers the substantiation questions to appear later in the CBI Substantiation portion of the form. See Table 4-13 for substantiation questions related to these data elements. **If you do not check the CBI box for any information element, then that information is not claimed as CBI and may be made public without further notice to you.** Further, if you fail to substantiate your CBI claims in accordance with the statute and applicable rules, EPA may make the information available to the public without further notice to you. For additional information about how to answer substantiation questions, visit *www.epa.gov/tsca-cbi* on the EPA website.

4.11.2 Manner or Method of Disposal

If the PFAS is disposed of, report the method of disposal using a code or codes from Table 4-23. Report all disposal controlled by the site (e.g., include shipments of waste for disposal to third parties). You are not required to report disposal by downstream users. Provide additional description of the disposal method as needed; additional description is required for code D99 "other." For each year, report any disposal methods(s) used during that year. You will be prompted to and are required to report disposal in any year from 2011 to 2022, even if you did not manufacture the PFAS in each year. For example, if you manufactured a PFAS in 2014, 2015, and 2016, and disposed of remaining waste containing that PFAS in 2017, you must include the disposal that occurred in 2017 even though you did not manufacture the PFAS that year.

If the PFAS is not disposed of in a given year, select "N/A" for that year. If you do not know and cannot reasonably ascertain whether the PFAS is disposed of, or if you know the PFAS is disposed of but do not know and cannot reasonably ascertain the method of disposal, select "NKRA."

Table 4-23. Disposal Process codes

Code	Description
D1	On-site land disposal: RCRA Class C landfill (hazardous)
D2	On-site land disposal: Other landfill

Code	Description
D3	Other on-site land disposal
D4	On-site underground injection (UIC)
D5	Off-site land disposal: RCRA Class C landfill (hazardous)
D6	Off-site land disposal: Other landfill
D7	On-site incineration
D8	Off-site incineration
D9	Publicly owned treatment works (POTW)
D10	Other off-site waste transfer
D11	On-site release to surface water
D12	On-site release to air (stack emissions)
D13	On-site release to air (fugitive emissions)
D99	Other

4.11.3 Changes in Disposal Methods

Use the free text field to describe any changes to the disposal process or methods since January 1, 2011.

4.11.4 Release Quantity

Report the total weight of the PFAS released to each medium (i.e., air, water, or land) in pounds. Report the quantity to at least two significant figures; it should be accurate to the extent known to or reasonably ascertainable by you. Release volumes should be reported in numeric format, without commas (e.g., 6352000). ***Report only the weight of the specific PFAS released***. Do not include the weight of any other materials (e.g., water, solvents, containers, or other chemical substances). Consider all possible sources of releases, including treated waste streams. For example, incineration of PFAS waste may not fully destroy the PFAS and there may be air releases of the PFAS associated with this process.

Table 4-24. Release media for disposal codes

Code	Description	Release Medium
D1	On-site land disposal: RCRA Class C landfill (hazardous)	Land
D2	On-site land disposal: Other landfill	Land
D3	Other on-site land disposal	Land
D4	On-site underground injection (UIC)	Land

Code	Description	Release Medium
D5	Off-site land disposal: RCRA Class C landfill (hazardous)	Land
D6	Off-site land disposal: Other landfill	Land
D7	On-site incineration	If combustion is incomplete, PFAS may remain in stack air emissions, ash, or scrubber blowdown, filter material, etc., and may be released to any medium
D8	Off-site incineration	Report off-site release media to the extent known to or reasonably ascertainable by you.
D9	Publicly owned treatment works (POTW)	Water
D10	Other off-site waste transfer	Report off-site release media to the extent known to or reasonably ascertainable by you.
D11	On-site release to surface water	Water
D12	On-site release to air (stack emissions)	Air
D13	On-site release to air (fugitive emissions)	Air
D99	Other	

4.11.5 Incineration Quantity and Temperature

Report the total weight of the PFAS incinerated on-site each year. If on-site incineration occurred, also report the incineration temperature (in degrees Celsius). If incineration occurred at multiple temperatures, indicate the minimum temperature (in degrees Celsius) at which the PFAS was incinerated. Report only the weight of PFAS destroyed by incineration. Quantities of PFAS not destroyed (e.g., released to air or remaining in ash) should be reported as releases in the previous section.

4.12 Optional Information

This section consists of a text field for submitting additional information. Use this field to provide any additional information about your submission that may be relevant.

4.13 Joint Submissions

4.13.1 Determining the Need for a Joint Submission

Joint submissions are required in those instances where a company (e.g., foreign supplier, contracting company) will not disclose to the manufacturer (including importer) certain chemical substance identifiers (i.e., CASRN, Accession number, or LVE number), due to confidentiality concerns.

This may happen, for instance, when a company is importing a mixture under a trade name, and the foreign manufacturer refuses to reveal the chemical identity of a confidential component of the mixture. In this case, the importer and the supplier can each separately report their portion of the required information, resulting in a joint submission. The importer must ask the supplier of the confidential chemical substance to directly provide EPA with the correct chemical identity (see 40 CFR 705.15(b)(iii)).

A manufacturer (including importer) can identify, on a chemical-by-chemical basis, the supplier for a chemical substance. The reporting tool will generate a unique ID number for each chemical substance (identified by a trade name). Therefore, a supplier may receive multiple ID numbers from a manufacturer (including importer). A supplier may also report multiple chemical substances under one ID number in the case that the ID number refers to a mixture. In that situation, the supplier will be identifying the PFAS that comprise the mixture.

It is the responsibility of the primary submitter to ask its supplier, or secondary submitter, to send the information to EPA by the end of the submission period. The reporting tool leads the primary submitter through this notification process.

If the secondary submitter decides to provide the required trade name product information directly to you, you should change your submission type and submit a single submission.

Note that not all submitters are required to initiate joint submissions. Article importers using the article importer reporting form will not be required or have the option to initiate joint *submissions.* Additionally, if a secondary submitter is not known or reasonably ascertainable to the PFAS manufacturer (e.g., if a foreign supplier is no longer in business and has no successor entity), then the manufacturer would indicate that the secondary submitter is NKRA and need not initiate a joint submission.

4.13.2 The Primary Submission is Completed by the PFAS Manufacturer

The primary submitter for a joint submission is either an importer or a manufacturer of a PFAS of unknown chemical identity (i.e., CASRN, TSCA Accession number, or LVE number). For ease of presentation, both types of primary submitters will be referred to as “importer.” The importer, as the primary submitter, is responsible for initiating the joint submission. The importer uses the reporting tool to notify the secondary submitter (e.g., its supplier or contract manufacturer) of the need to complete the secondary portion of the joint submission, and completes the sections related to manufacturing (Part II.A – C), processing and use (Part II.D), byproducts (Part II.D), environmental and health effects (Part II.E), (40 CFR 705.15(f)) and the processing and use-related section (Part II.D) (40 CFR 705.15(c)) for the imported substance.

Identifying the chemical identity of the unknown chemical substance and its secondary submitter

In its portion of the joint submission, the primary submitter identifies the proprietary substance or mixture using the trade name or another name, additional information as needed to help the secondary submitter correctly identify the substance, and the identity and contact information for the secondary submitter. See Sections 4.4.2 and 4.5.11 for additional information.

Notifying the secondary submitter about the joint submission

Using the reporting tool, the importer enters the email address of the secondary submitter, and any necessary instruction for the secondary submitter to complete its part of the joint submission, into a system generated email. Also contained within the email is the unique identifier. The importer will need to click the link to send this information from CDX to the Secondary Authorized Official. Additional recipients may be added by the importer. The primary submitter may send the email before it has completed its part of the joint submission.

Completing the primary portion of the joint submission

The importer is responsible for completing the rest of Part II of the form as it relates to the proprietary substance or mixture. See Sections 4.7 through 4.12 of this document for additional information about completing Part II.

4.13.3 The Secondary Submission is Completed

The secondary submitter is responsible for identifying that it is providing information for the joint submission using the information (e.g., identification number) provided by the primary submitter and completing the Secondary Form.

4.13.3.1 Receiving notification from the primary submitter about the joint submission

The secondary submitter receives an email from the primary submitter identifying that a joint submission has been initiated and providing the unique identification number needed for the secondary submitter to complete its part of the joint submission.

4.13.3.2 Completing the Secondary Form, the secondary portion of the joint submission

The secondary submitter is responsible for completing the Secondary Form of the joint submission, which includes its company identity, a technical contact, identification of its customer (i.e., the primary submitter), the product trade name, and the unique identifier supplied by the primary submitter. The secondary submitter then provides the chemical identity and percentage of formulation of each PFAS in the product. See Section 4.54.5 for information about chemical identity.

4.13.3.3 When the Supplier Doesn’t Know the Chemical Identity

There may be instances where a foreign supplier (i.e., secondary submitter) purchases a mixture, under a trade name, from another company (tertiary company) and does not know the chemical components of the mixture. The foreign supplier can ask the company manufacturing the trade secret mixture or chemical substance to directly provide EPA with the correct chemical identity. In this case, the tertiary company would register with CDX and use the Unique Identifier for Joint Submissions, sent to the foreign supplier by the manufacturer (including importer), to complete the form.

Under this scenario, the foreign supplier does not have access to any of the information submitted to EPA by the tertiary company. Likewise, the tertiary company cannot see the information the foreign supplier reports to EPA. This way, the confidentiality of information for both the foreign supplier and tertiary company is protected.

4.13.4 Confidentiality of Information Jointly Submitted

All of the confidentiality requirements discussed earlier in these Instructions apply to information submitted jointly. However, joint submissions include information required to connect the two reports and their related data. For example, a joint submission requires that the primary submitter provide a generic chemical name or trade name and secondary submitter's identity. A secondary submitter would provide the composition of its product.

These data elements specific to joint submissions require that any claims of confidentiality be asserted at the time of submission, but do not require upfront substantiation (pursuant to TSCA section 14(c)(2)):

- Joint submission information from the primary submitter consisting of trade name and supplier identification required pursuant to § 705.15(b)(1)(i) and § 705.18(b)(2)(i).
- Joint submission information from the secondary submitter consisting of the percentage of formulation required pursuant to § 705.15(b)(1)(i) and (ii).

Because signatures are required by each party of a joint submission, each party must register with CDX and complete their own sections of the same report. The reporting tool will match both submissions based upon the unique ID number sent by the manufacturer (including importer) to notify the secondary submitter of the partial section 8(a)(7) submission. Suppliers do not have access to any of the information submitted to EPA by the manufacturer (except the manufacturer's identity and contact information and the submitted trade name or chemical identifier) . Likewise, manufacturers cannot see the information that the supplier reports to EPA.

This way, the confidentiality of information for all submitters is protected. The information provided by both submitters will be combined and processed as one joint submission once they are received by EPA.

NOTE: In the event that a manufacturer (including importer) actually knows or can reasonably ascertain the chemical identity (e.g., the CASRN or Accession Number) of a chemical substance subject to section 8(a)(7) reporting, the manufacturer (including importer) must provide that information irrespective of a supplier's confidentiality claims. If

such a primary submitter wishes to claim the chemical identity as confidential, to do so they must check the CBI box and provide upfront substantiation as described in 4.5.1 of this chapter.

5. How to Obtain Copies of Documents Cited in This Instructions Document

5.1 Obtaining Copies of the TSCA Rules

The section 8(a)(7) rule, *40 CFR 705*, is available on the U.S. Government Publishing Office website, *www.ecfr.gov*.

You may also contact the TSCA Hotline by telephone at (202) 554-1404 or by email tsca-hotline@epa.gov for assistance.

5.2 Obtaining Copies of Other Information Materials

EPA has developed documents to provide additional information on submitting information for this data call. Except where otherwise noted, materials are available on the section 8(a)(7) website at *https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/tsca-section-8a7-reporting-and- recordkeeping*. In addition to materials developed specifically for section 8(a)(7) reporting, some materials developed for TSCA more broadly or for CDR reporting are also applicable to reporting under this data call.

Reporting Electronically:

- Instructions on CDX registration: *CDX Online Registration User Guide*
- Some fact sheets Fact Sheets for CDR are relevant to section 8(a)(7) reporting. These fact sheets are available at *How To Report Under Chemical Data Reporting*. CDR fact sheets relevant to reporting under this data call include:
- *Reporting After Changes to Company Ownership or Legal Identity*
- *Imported Articles* (use this fact sheet as guidance in determining if your chemical substance is contained in an article; other items discussed in this fact sheet, such as references to reporting thresholds and polymer exemption, do not apply to this data call)

Appendix A. Glossary of Terms

The definitions and descriptions of terms used in section 8(a)(7) reporting provided below are taken from 40 CFR Part 711 unless otherwise noted.

Act means the Toxic Substances Control Act, as amended, 15 U.S.C. 2601 *et seq*.

Administrator means the Administrator of the Environmental Protection Agency. (See TSCA 3(1))

Article means a manufactured item (1) which is formed to a specific shape or design during manufacture, (2) which has end-use function(s) dependent in whole or in part upon its shape or design during end use, and (3) which has either no change of chemical composition during its end use or only those changes of composition which have no commercial purpose separate from that of the article, and that result from a chemical reaction that occurs upon end use of other chemical substances, mixtures, or articles; except that fluids and particles are not considered articles regardless of shape or design. (40 CFR 704.3)

Byproduct means a chemical substance produced without separate commercial intent during the manufacture, processing, use, or disposal of another chemical substance(s) or mixture(s). (40 CFR 704.3)

Central Data Exchange (CDX) means EPA's centralized electronic document receiving system, or its successors, including associated instructions for registering to submit electronic documents.

Chemical Information Submission System (CISS) means EPA's electronic, web-based reporting tool for the completion and submission of data, reports, and other information, or its successors.

Chemical substance means any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature, and any element or uncombined radical. “Chemical substance” does *not* include:

(1) Any mixture;

(2) Any pesticide (as defined in the Federal Insecticide, Fungicide, and Rodenticide Act) when manufactured, processed, or distributed in commerce for use as a pesticide;

(3) Tobacco or any tobacco product;

(4) Any source material, special nuclear material, or byproduct material (as such terms are defined in the Atomic Energy Act of 1954 [42 U.S.C. 2011 et seq.] and the regulations issued under such Act);

(5) Any article the sale of which is the subject to the tax imposed by section 4181 of the Internal Revenue Code of 1986 [26 U.S.C. 4181] (determined without regard to any

exemptions from such tax provided by section 4182 or 4221 or any other provision of such Code) and any component of such an article (limited to shot shells, cartridges, and components of shot shells and cartridges); and

(6) Any food, food additive, drug, cosmetic, or device (as such terms are defined in section 201 of the Federal Food, Drug, and Cosmetic Act [21 U.S.C. 321]) when manufactured, processed, or distributed in commerce for use as a food, food additive, drug, cosmetic, or device. (See TSCA 3(2))

Commerce means trade, traffic, transportation, or other commerce: (A) between a place in a State and any place outside of such State, or (B) which affects trade, traffic, transportation, or commerce described in clause (A). (TSCA 3(3))

Commercial use means the use of a chemical substance or a mixture containing a chemical substance (including as part of an article) in a commercial enterprise providing saleable goods or services.

Consumer use means the use of a chemical substance or a mixture containing a chemical substance (including as part of an article) when sold to or made available to consumers for their use.

Customs territory of the United States, as referenced in TSCA section 3 and defined in general note 2 of the Harmonized Tariff Schedule of the United States, includes only the States, the District of Columbia, and Puerto Rico.

Distribute in commerce and distribution in commerce, when used to describe an action taken with respect to a chemical substance or mixture or article containing a substance or mixture mean to sell, or the sale of, the substance, mixture, or article in commerce; to introduce or deliver for introduction into commerce, or the introduction or delivery for introduction into commerce of, the substance, mixture, or article; or to hold, or the holding of, the substance, mixture, or article after its introduction into commerce. (TSCA 3(5))

Environmental or health effects information means any information of any effect of a chemical substance or mixture containing a chemical substance on health or the environment or on both. This includes all health and safety studies.

(1) Not only is information that arises as a result of a formal, disciplined study included, but other information relating to the effects of a chemical substance or mixture containing a chemical substance on health or the environment is also included. Any information that bears on the effects of a chemical substance on health or the environment would be included.

(2) Examples are:

  (i) Long- and short-term tests of mutagenicity, carcinogenicity, or teratogenicity; data on behavioral disorders; dermatoxicity; pharmacological effects;

mammalian absorption, distribution, metabolism, and excretion; cumulative, additive, and synergistic effects; and acute, subchronic, and chronic effects.

(ii) Tests for ecological or other environmental effects on invertebrates, fish, or other animals, and plants, including: Acute toxicity tests, chronic toxicity tests, critical life-stage tests, behavioral tests, algal growth tests, seed germination tests, plant growth or damage tests, microbial function tests, bioconcentration or bioaccumulation tests, and model ecosystem (microcosm) studies.

(iii) Assessments of human and environmental exposure, including workplace exposure, and impacts of a particular chemical substance or mixture containing a chemical substance on the environment, including surveys, tests, and studies of: Biological, photochemical, and chemical degradation; structure/activity relationships; air, water, and soil transport; biomagnification and bioconcentration; and chemical and physical properties, e.g., boiling point, vapor pressure, evaporation rates from soil and water, octanol/water partition coefficient, and water solubility.

(iv) Monitoring data, including but not limited to when they have been aggregated and analyzed to measure the exposure of humans or the environment to a chemical substance or mixture containing a chemical substance. (40 CFR 705.15)

EPA means the United States Environmental Protection Agency. (40 CFR 704.3)

Health and safety studies means any study of any effect of a chemical substance or mixture on health or the environment or on both, including underlying information and epidemiological studies, studies of occupational exposure to a chemical substance or mixture, toxicological, clinical, and ecological studies of a chemical substance or mixture containing a chemical substance, and any test performed under TSCA. [15 U.S.C. 2602(8)]

Highest-level Parent Company means the highest-level company of the site's ownership hierarchy as of the start of the submission period during which data are being reported according to the following instructions. The highest-level U.S. parent company is located within the United States while the highest-level foreign parent company is located outside the United States. The following rules govern how to identify the highest-level U.S. parent company and highest-level foreign parent company (if applicable):

(1) If the site is entirely owned by a single U.S. company that is not owned by another company, that single company is the U.S. parent company.

(2) If the site is entirely owned by a single U.S. company that is, itself, owned by another U.S.-based company (e.g., it is a division or subsidiary of a higher-level company), the highest- level domestic company in the ownership hierarchy is the United States parent company. If there is a higher-level parent company that is outside of the United States, the highest-level foreign company in the ownership hierarchy is the foreign parent company.

(3) If the site is owned by more than one company (e.g., company A owns 40 percent, company B owns 35 percent, and company C owns 25 percent), the company with the largest ownership interest in the site is the parent company. If a higher-level company in the ownership hierarchy owns more than one ownership company, then determine the entity with the largest ownership by considering the lower-level ownerships in combination (e.g., corporation X owns companies B and C, for a total ownership of 60 percent for the site).

(4) If the site is owned by a 50:50 joint venture or a cooperative, the joint venture or cooperative is its own parent company. If the site is owned by a U.S. joint venture or cooperative, the highest level of the joint venture or cooperative is the U.S. parent company. If the site is owned by a joint venture or cooperative outside the United States, the highest level of the joint venture or cooperative outside the United States is the foreign parent company.

(5) If the site is federally owned, the highest-level federal agency or department is the U.S. parent company.

(6) If the site is owned by a non-federal public entity, that entity (such as a municipality, State, or tribe) is the U.S. parent company.

Importer means

(1) any person who imports any chemical substance or any chemical substance as part of a mixture or article into the customs territory of the United States, and includes:
    (i) the person primarily liable for the payment of any duties on the merchandise, or
    (ii) an authorized agent acting on his/her behalf.

(2) Importer also includes, as appropriate:
    (i) The consignee.
    (ii) The importer of record.
    (iii) The actual owner if an actual owner's declaration and superseding bond have been filed in accordance with 19 CFR 141.20.
    (iv) The transferee, if the right to draw merchandise in a bonded warehouse has been transferred in accordance with subpart C of 19 CFR part 144.

(3) For the purposes of this definition, the customs territory of the United States consists of the 50 States, Puerto Rico, and the District of Columbia. (40 CFR 704.3)

Impurity means a chemical substance which is unintentionally present with another chemical substance. (40 CFR 704.3)

Industrial function means the intended physical or chemical characteristic for which a chemical substance or mixture is consumed as a reactant; incorporated into a formulation, mixture, reaction product, or article; repackaged; or used.

Industrial use means use at a site at which one or more chemical substances or mixtures are manufactured (including imported) or processed.

Intended for use by children means the chemical substance or mixture is used in a product that is specifically intended for use by children age 14 or younger. A chemical substance or mixture is intended for use by children when the submitter answers "yes" to at least one of the following questions for the product into which the submitter's chemical substance or mixture is incorporated:

(1) Is the product commonly recognized (i.e., by a reasonable person) as being intended for children aged 14 or younger?

(2) Does the manufacturer of the product state through product labeling or other written materials that the product is intended or will be used by children age 14 or younger?

(3) Is the advertising, promotion, or marketing of the product aimed at children age 14 or younger?

Intermediate means any chemical substance that is consumed, in whole or in part, in chemical reactions used for the intentional manufacture of other chemical substances or mixtures, or that is intentionally present for the purpose of altering the rates of such chemical reactions. (40 CFR 704.3)

Known to or reasonably ascertainable by means all information in a person's possession or control, plus all information that a reasonable person similarly situated might be expected to possess, control, or know. (40 CFR 704.3)

Manufacture means to manufacture, produce, or import, for commercial purposes. Manufacture includes the extraction, for commercial purposes, of a component chemical substance from a previously existing chemical substance or complex combination of substances. A chemical substance is co-manufactured by the person who physically performs the manufacturing and the person contracting for such production when that chemical substance, manufactured other than by import, is: (1) produced exclusively for another person who contracts for such production, and (2) that other person dictates the specific identity of the chemical substance and controls the total amount produced and the basic technology for the manufacturing process. [15 U.S.C. 2602(9)]

Manufacturer means a person who manufactures a chemical substance.

Manufacture for commercial purposes means: (1) to import, produce, or manufacture with the purpose of obtaining an immediate or eventual commercial advantage for the manufacturer, and includes among other things, such “manufacture” of any amount of a chemical substance or mixture:

(i) For commercial distribution, including for test marketing.

(ii) For use by the manufacturer, including use for product research and development, or as an intermediate.

(2) Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose. (40 CFR 704.3)

Master Inventory File means EPA's comprehensive list of chemical substances which constitute the Chemical Substances Inventory compiled under section 8(b) of the Act. It includes substances reported under 40 CFR Part 710 and substances reported under Part 720 for which a Notice of Commencement of Manufacture or Import has been received under § 720.120.

Microorganism means any combination of chemical substances that is a living organism and that meets the definition of microorganism at 40 CFR 725.3. Any chemical substance produced from a living microorganism is reportable under the CDR regulation unless otherwise excluded.

Mixture means any combination of two or more chemical substances if the combination does not occur in nature and is not, in whole or in part, the result of a chemical reaction; except that such term does include any combination which occurs, in whole or in part, as a result of a chemical reaction if none of the chemical substances comprising the combination is a new chemical substance and if the combination could have been manufactured for commercial purposes without a chemical reaction at the time the chemical substances comprising the combination were combined. (TSCA 3(10))

Naturally occurring substance is any chemical substance which is naturally occurring and: (1) which is (i) unprocessed or (ii) processed only by manual, mechanical, or gravitational means, by dissolution in water, by flotation, or by heating solely to remove water; or (2) which is extracted from air by any means. (40 CFR 710.4(b))

Non-isolated intermediate means any intermediate that is not intentionally removed from the equipment in which it is manufactured, including the reaction vessel in which it is manufactured, equipment which is ancillary to the reaction vessel, and any equipment through which the substance passes during a continuous flow process, but not including tanks or other vessels in which the substance is stored after its manufacture. (40 CFR 704.3)

Parent Company is a company that owns or controls another company. (40 CFR 704.3)

Per- and polyfluoroalkyl substances or **PFAS**, means any chemical substance or mixture containing a chemical substance that structurally contains at least one of the following three sub-structures:

1. R-(CF_2)-CF(R’)R’’, where both the CF_2 and CF moieties are saturated carbons
2. R-CF_2OCF_2-R’, where R and R’ can either be F, O, or saturated carbons
3. $CF_3C(CF_3)$R’R’’, where R’ and R”” can either be F or saturated carbons. (40 CFR 705.15)

Person means any individual, firm, company, corporation, joint venture, partnership, sole proprietorship, association, or any other business entity; any State or political subdivision thereof, or any municipality; any interstate body; and any department, agency, or instrumentality of the Federal government. (40 CFR 704.3)

Polymer means any chemical substance described with the word fragments “*polym*”, “*alkyd”, or “oxylated” in the Chemical Abstracts (CA) Index Name in the Master Inventory File, where the asterisk (*) in the listed word fragments indicates that any sets of characters may precede, or follow, the character string defined. Polymers also include any chemical substance which is identified in the Master Inventory File as siloxane(s) and silicone(s), silsesquioxane(s), a protein (albumin, casein, gelatin, gluten, hemoglobin), an enzyme, a polysaccharide (starch, cellulose, or gum), rubber, or lignin. The polymer exclusion does not apply to a polymeric substance that has been hydrolyzed, depolymerized, or otherwise chemically modified, except in cases where the intended product of this reaction is totally polymeric in structure.

Possession or control means in possession or control of the submitter, or of any subsidiary, partnership in which the submitter is a general partner, parent company, or any company or partnership which the parent company owns or controls, if the subsidiary, parent company, or other company or partnership is associated with the submitter in the research, development, test marketing, or commercial marketing of the chemical substance in question. (A parent company owns or controls another company if the parent owns or controls 50 percent or more of the other company's voting stock. A parent company owns or controls any partnership in which it is a general partner). Information is included within this definition if it is:

(1) In files maintained by submitter's employees who are:

  (i) Associated with research, development, test marketing, or commercial marketing of the chemical substance in question.

  (ii) Reasonably likely to have such data.

(2) Maintained in the files of other agents of the submitter who are associated with research, development, test marketing, or commercial marketing of the chemical substance in question in the course of their employment as such agents. (40 CFR 705.15)

Process means to process for commercial purposes. (40 CFR 704.3)

Process for commercial purposes means the preparation of a chemical substance or mixture after its manufacture for distribution in commerce with the purpose of obtaining an immediate or eventual commercial advantage for the processor. Processing of any amount of a chemical substance or mixture is included in this definition. If a chemical substance or mixture containing impurities is processed for commercial purposes, then the impurities also are processed for commercial purposes. (40 CFR 704.3)

Processor means any person who processes a chemical substance or mixture. (40 CFR 704.3)

Reasonably likely to be exposed means an exposure to a chemical substance which, under foreseeable conditions of manufacture (including import), processing, distribution in commerce, or use of the chemical substance, is more likely to occur than not to occur. Such exposures would normally include, but would not be limited to, activities such as charging reactor vessels, drumming, bulk loading, cleaning equipment, maintenance operations, materials handling and transfers, and analytical operations. Covered exposures include exposures through any route of entry (inhalation, ingestion, skin contact, absorption, etc.), but excludes accidental or theoretical exposures.

Repackaging means the physical transfer of a chemical substance or mixture, as is, from one container to another container or containers in preparation for distribution of the chemical substance or mixture in commerce.

Reportable chemical substance means a chemical substance described in § 711.5.

Research and development (R&D) means activities intended solely as scientific experimentation, research, or analysis. R&D focuses on the analysis of the chemical or physical characteristics, the performance, or the production characteristics of a chemical substance, a mixture containing the substance, or an article. R&D encompasses a wide range of activities which may occur in a laboratory, pilot plant, commercial plant outside the research facility, or at other sites appropriate for R&D. General distribution of chemical substances to consumers does not constitute R&D. (40 CFR 705.15)

Site means a contiguous property unit. Property divided only by a public right-of-way shall be considered one site. More than one plant may be located on a single site.

(a) For chemical substances manufactured under contract, i.e., by a co-manufacturer, the site is the location where the chemical substance is physically manufactured.

(b) The site for an importer who imports a chemical substance described in § 711.5 is the U.S. site of the operating unit within the person's organization that is directly responsible for importing the substance. The import site, in some instances, may be the organization's headquarters in the United States. If there is no such operating unit or headquarters in the United States, the site address for the importer is the

United States address of an agent acting on behalf of the importer who is authorized to accept service of process for the importer.

(c) For portable manufacturing units sent out to different locations from a single distribution center, the distribution center shall be considered the site.

Site-limited means a chemical substance is manufactured and processed only within a site and is not distributed for commercial purposes as a substance or as part of a mixture or article outside the site. Imported substances are never site-limited. Although a site-limited chemical substance is not distributed for commercial purposes outside the site at which it is manufactured and processed, the substance is considered to have been manufactured and processed for commercial purposes.

Small government means the government of a city, county, town, township, village, school district, or special district with a population of less than 50,000. (40 CFR 704.3)

Small manufacturer means a manufacturer (including importer) that meets either of the following standards:

(1) *First standard.* A manufacturer (including importer) of a substance is small if its total annual sales, when combined with those of its parent company (if any), are less than $120 million. However, if the annual production or importation volume of a particular substance at any individual site owned or controlled by the manufacturer or importer is greater than 45,400 kilograms (100,000 lbs), the manufacturer (including importer) will not qualify as small for purposes of reporting on the production or importation of that substance at that site, unless the manufacturer (including importer) qualifies as small under standard (2) of this definition.

(2) *Second standard.* A manufacturer (including importer) of a substance is small if its total annual sales, when combined with those of its parent company (if any), are less than $12 million, regardless of the quantity of substances produced or imported by that manufacturer (including importer). (40 CFR 704.3)

Small quantities solely for research and development (or “small quantities solely for purposes of scientific experimentation or analysis or chemical research on, or analysis of, such substance or another substance, including such research or analysis for the development of a product”) means quantities of a chemical substance manufactured, imported, or processed or proposed to be manufactured, imported, or processed solely for research and development that are no greater than reasonably necessary for such purposes. (40 CFR 704.3)

State means any State of the United States, the District of Columbia, the Commonwealth of Puerto Rico, the Virgin Islands, Guam, the Canal Zone, American Samoa, the Northern Mariana Islands, or any other territory or possession of the United States. (TSCA 3(16))

Submission period means the period in which data are submitted to EPA.

United States, when used in the geographic sense, means all of the States. (TSCA3(17))

Use means any utilization of a chemical substance or mixture that is not otherwise covered by the terms *manufacture* or *process*. Relabeling or redistributing a container holding a chemical substance or mixture where no repackaging of the chemical substance or mixture occurs does not constitute use or processing of the chemical substance or mixture.

Worker means someone at a site of manufacture, import, or processing who performs work activities near sources of a chemical substance or mixture or directly handles the chemical substance or mixture during the performance of work activities. (40 CFR 705.15)

Appendix B. Key Comparisons between Section 8(a)(7) Data Call and CDR

This PFAS data call is promulgated under TSCA section 8(a)(7) and has many similarities to Chemical Data Reporting (CDR) required under TSCA section 8(a)(1). You or someone else at your site or company may have previously reported to CDR. However, it is important to note that there are certain differences between section 8(a)(7) reporting and reporting under CDR. You should review the final rule in 40 CFR 705 as well as this document to ensure you are reporting correctly. To assist you, this section outlines key differences between section 8(a)(7) reporting and reporting under CDR. Important differences to consider include:

- Absence of certain reporting exemptions and reporting thresholds that exist under CDR
- Differences in what data elements are to be reported
- Timeframe (years covered by the rule)
- Considerations for claiming information as confidential business information (CBI)
- Availability of streamlined reporting options in certain manufacturing scenarios

Reporting Exemptions

PFAS section 8(a)(7) reporting does not provide any exemptions. Do not assume you qualify for a section 8(a)(7) exemption because you qualify for a CDR exemption. Review Section 2 of this document for additional guidance on determining if you are required to report. For example, CDR reporters are not required to report for small manufacture/import quantities, chemicals imported as part of an article, or chemicals manufactured as byproducts that meet exemption requirements under 711.10(c), 711.10 (d)(1), or 711.10(d)(2). ***No such exemptions apply to section 8(a)(7) reporting – you may be required to submit a section 8(a)(7) report even if one of these, or any other, CDR exemption applies to your chemical substance.***

CDR exemptions that ***do not apply*** to PFAS Section 8(a)(7) reporting include, but are not limited to, exemptions for: articles containing PFAS (including imported articles containing PFAS such as articles containing PFAS as part of surface coatings), byproducts, impurities, polymers, and non-isolated intermediates.

Reported Data Elements

Data to be reported under section 8(a)(7) include some fields comparable to data reporting under CDR and some additional data. For fields comparable to CDR reporting, note that there may be differences between requirements for how to report to this data call compared to CDR reporting. In particular, lists of codes (such as codes for reporting industrial uses) may differ from the codes your site has used to report to CDR in the past. Additional data to be reported includes information on byproducts, environmental and health effects, worker exposure during industrial and commercial use, and disposal.

Covered Timeframe

This data call covers activities occurring from January 1, 2011, through December 31, 2022 (i.e., the end of the last calendar year prior to the effective date of this rule), a period of 12 years. Unlike CDR reporting, all years are treated equally for purposes of this data call; there is no “principal reporting year,” and the same data elements must be reported for each year. The reporting software allows you to select a subset of years to report on if you did not manufacture the PFAS every year.

Considerations for CBI claims

Although the process of asserting CBI claims is similar to the process used for CDR reporting, there are some important differences. Review the section 8(a)(7) rule and this guidance when asserting CBI claims. It is your responsibility to ensure you are claiming and substantiating CBI claims **as required by the section 8(a)(7) rule**. If you fail to substantiate your CBI claims in accordance with the statute and applicable rules, EPA may make the information available to the public without further notice to you. However, EPA intends to publish a list of Accession numbers for which either no chemical identity CBI claim was asserted or the claim was denied as candidates for moving to the public Inventory and provide opportunity for other claimants of the chemical identity to appeal. Instructions for claiming and substantiating CBI claims are included in the instructions for each section. For additional information about how to answer substantiation questions, visit *www.epa.gov/tsca-cbi* on the EPA website.

Appendix C. Examples of PFAS covered by this rule

The requirements of this part apply to all chemical substances and mixtures that are PFAS, consistent with the definition of PFAS at § 705.3. A non-exhaustive list of PFAS is provided in EPA's CompTox Dashboard. The CompTox list includes all chemicals with known structures that meet the definition of PFAS for section 8(a)(7) reporting. The CompTox list includes all known chemicals, regardless of their TSCA Inventory status, and is updated as new chemicals are added to the database. The CompTox list does not include all polymers or chemicals with undefined (unknown or variable) structures, which may be covered by this rule. This list is also available via EPA's Substance Registry Service. An Excel® file of chemicals on the TSCA Inventory that meet the definition of PFAS is provided in the Additional Resources section of the PFAS 8(a)(7) website: https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/tsca-section-8a7-reporting-and-recordkeeping#additional-resources. The Excel® file includes both chemicals with known structures as well as polymers and other chemicals with unknown or variable composition.

Note that this rule defines PFAS using a structural definition. While EPA is providing these lists to assist potentially affected entities with identifying reportable PFAS, manufacturers are advised that a chemical substance's omission from these lists does not necessarily mean it is not reportable under this rule. EPA notes that some possible reasons that a TSCA chemical substance that meets this rule's PFAS definition include: (1) being exempt from other TSCA reporting or notification requirements (e.g., certain byproducts, impurities, R&D substances); (2) a substance whose identity (even a generic identity) EPA cannot currently reveal due to confidential business information (CBI) protections.

Appendix D. Descriptions of Codes for Reporting Processing or Use Operations, Industrial Sectors, Function Categories, and Consumer and Commercial Product Categories

The following descriptions were developed by EPA to assist persons submitting information in response to 40 CFR 711.15(c) and reported in Part II.D of the section 8(a)(7) reporting. Table D-3Table D-3, Table D-4, Table D-5and Table D-6Table D-6 include crosswalks between OECD standardized codes to be used for section 8(a)(7) reporting and codes used for reporting to CDR.

For more information, see the Technical Support Document: “Harmonizing CDR Functional and Product codes with OECD Functional, Product, and Article Codes,” located in the rulemaking record (EPA-HQ-OPPT-2018-0321).

Table D-1 provides the type of processing or use operation (TPU) codes with descriptions of the types of operations. These codes are used to report in Part II, Section B.

Table D-1. Type of Processing or Use Operation and Descriptions

Code	Type of Operation	Description
PC	Processing as a reactant	Chemical substance is used in chemical reactions for the manufacturing of another chemical substance or product.
PF	Processing—incorporation into formulation, mixture, or reaction product	Chemical substance is added to a product (or product mixture) prior to further distribution of the product.
PA	Processing—incorporation into article	Chemical substance becomes an integral component of an article distributed for industrial, trade, or consumer use.
PK	Processing—repackaging	Preparation of a chemical substance for distribution in commerce in a different form, state, or quantity. This includes transferring the chemical substance from a bulk container into smaller containers. This definition does not apply to sites that only relabel or redistribute the reportable chemical substance without removing the chemical substance from the container in which it is received or purchased.
U	Use—non-incorporative activities	Chemical substance is otherwise used (e.g., as a chemical processing or manufacturing aid).

Table D-2 provides a crosswalk between Industrial Sector (IS) codes used to report in Part II Section B with North American Industrial Classification System (NAICS) codes commonly used to classify businesses.

Table D-2. Industrial Sector (IS) Code Descriptions with NAICS Crosswalk

NAICS	IS Code	IS Title
11	IS1	Agriculture, Forestry, Fishing and Hunting
211	IS2	Oil and Gas Drilling, Extraction, and Support Activities
213		
212	IS3	Mining (except Oil and Gas) and Support Activities
22	IS4	Utilities
23	IS5	Construction
311	IS6	Food, beverage, and tobacco product manufacturing
312		
313	IS7	Textiles, apparel, and leather manufacturing
314		
315		
316		
321	IS8	Wood Product Manufacturing
322	IS9	Paper Manufacturing
323	IS10	Printing and Related Support Activities
32411	IS11	Petroleum Refineries
32412	IS12	Asphalt Paving, Roofing, and Coating Materials Manufacturing
324191	IS13	Petroleum Lubricating Oil and Grease Manufacturing
324199	IS14	All Other Petroleum and Coal Products Manufacturing
32511	IS15	Petrochemical Manufacturing
32512	IS16	Industrial Gas Manufacturing
32513	IS17	Synthetic Dye and Pigment Manufacturing
325182	IS18	Carbon Black Manufacturing
32518	IS19	All Other Basic Inorganic Chemical Manufacturing
325192	IS20	Cyclic Crude and Intermediate Manufacturing
32519	IS21	All Other Basic Organic Chemical Manufacturing
325211	IS22	Plastic Material and Resin Manufacturing

NAICS	IS Code	IS Title
325212	IS23	Synthetic Rubber Manufacturing
32522	IS24	Organic Fiber Manufacturing
3253	IS25	Pesticide, Fertilizer, and Other Agricultural Chemical Manufacturing
3254	IS26	Pharmaceutical and Medicine Manufacturing
32551	IS27	Paint and Coating Manufacturing
32552	IS28	Adhesive Manufacturing
3256	IS29	Soap, Cleaning Compound, and Toilet Preparation Manufacturing
32591	IS30	Printing Ink Manufacturing
32592	IS31	Explosives Manufacturing
325991	IS32	Custom Compounding of Purchased Resin
325992	IS33	Photographic Film Paper, Plate, and Chemical Manufacturing
325998	IS34	All Other Chemical Product and Preparation Manufacturing
3261	IS35	Plastics Product Manufacturing
3262	IS36	Rubber Product Manufacturing
327	IS37	Nonmetallic Mineral Product Manufacturing (includes clay, glass, cement, concrete, lime, gypsum, and other nonmetallic mineral product manufacturing)
331	IS38	Primary Metal Manufacturing
332	IS39	Fabricated Metal Product Manufacturing
333	IS40	Machinery Manufacturing
334	IS41	Computer and Electronic Product Manufacturing
335	IS42	Electrical Equipment, Appliance, and Component Manufacturing
336	IS43	Transportation Equipment Manufacturing
337	IS44	Furniture and Related Product Manufacturing
339	IS45	Miscellaneous Manufacturing
42	IS46	Wholesale and Retail Trade
44		
45		
48		
49		
51	IS47	Services
52		
53		
54		
55		

NAICS	IS Code	IS Title
56		
61		
62		
71		
72		
81		
92		
	IS48	Other (requires additional information)

Table D-3 provides the 2020 CDR Product Category codes (based on OECD harmonized codes) to be used for section 8(a)(7) reporting, with corresponding product category codes from 2016 CDR reporting. The 2016 CDR codes are provided only as a reference to assist you if your company has used these codes in past reporting. Do not use 2016 CDR codes for section 8(a)(7) reporting.

Table D-3. Product Category Codes

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.			
Column A: Section 8(a)(7) codes		**Column B: 2016 CDR codes**	
Code	**Category**	**Code**	**Category**
Chemical Substances in Furnishing, Cleaning, Treatment Care Products			
CC101	Construction and building materials covering large surface areas including stone, plaster, cement, glass and ceramic articles; fabrics, textiles, and apparel	C101	Floor coverings
CC102	Furniture & furnishings including plastic articles (soft); leather articles	C102	Foam seating and bedding products
CC103	Furniture & furnishings including stone, plaster, cement,glass and ceramic articles; metal articles; or rubber articles	C103	Furniture and furnishings not covered elsewhere
CC104	Leather conditioner	C104	Fabric, textile, and leather products not covered elsewhere
CC105	Leather tanning, dye, finishing, impregnation and care products		
CC106	Textile (fabric) dyes		
CC107	Textile finishing and impregnating/surface treatment products		
CC108	All-purpose foam spray cleaner	C105	Cleaning and furnishing care products
CC109	All-purpose liquid cleaner/polish		
CC110	All-purpose liquid spray cleaner		
CC111	All-purpose waxes and polishes		
CC112	Appliance cleaners		
CC113	Drain and toilet cleaners (liquid)		
CC114	Powder cleaners (floors)		
CC115	Powder cleaners (porcelain)		
CC116	Dishwashing detergent (liquid/gel)	C106	Laundry and dishwashing products
CC117	Dishwashing detergent (unit dose/granule)		
CC118	Dishwashing detergent liquid (hand-wash)		
CC119	Dry cleaning and associated products		

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.			
Column A: Section 8(a)(7) codes		**Column B: 2016 CDR codes**	
Code	**Category**	**Code**	**Category**
CC120	Fabric enhancers		
CC121	Laundry detergent (unit-dose/granule)		
CC122	Laundry detergent (liquid)		
CC123	Stain removers		
CC124	Ion exchangers	C107	Water treatment products
CC125	Liquid water treatment products		
CC126	Solid/Powder water treatment products		
CC127	Liquid body soap	C108	Personal care products
CC128	Liquid hand soap		
CC129	Solid bar soap		
CC130	Air fresheners for motor vehicles	C109	Air care products
CC131	Continuous action air fresheners		
CC132	Instant action air fresheners		
CC133	Anti-static spray	C110	Apparel and footwear care products
CC134	Apparel finishing, and impregnating/surface treatment products		
CC135	Insect repellent treatment		
CC136	Pre-market waxes, stains, and polishes applied to footwear		
CC137	Post-market waxes, and polishes applied to footwear (shoe polish)		
CC138	Waterproofing and water-resistant sprays		
Chemical Substances in Construction, Paint, Electrical, and Metal Products			
CC201	Fillers and putties	C201	Adhesives and sealants
CC202	Hot-melt adhesives		
CC203	One-component caulks		
CC204	Solder		
CC205	Single-component glues and adhesives		
CC206	Two-component caulks		
CC207	Two-component glues and adhesives		
CC208	Adhesive/Caulk removers	C202	Paints and coatings

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.			
Column A: Section 8(a)(7) codes		**Column B: 2016 CDR codes**	
Code	**Category**	**Code**	**Category**
CC209	Aerosol spray paints		
CC210	Lacquers, stains, varnishes and floor finishes		
CC211	Paint strippers/removers		
CC212	Powder coatings		
CC213	Radiation curable coatings		
CC214	Solvent-based paint		
CC215	Thinners		
CC216	Water-based paint		
CC217	Construction and building materials covering large surface areas, including wood articles	C203	Building/ construction materials - wood and engineered wood products
CC218	Construction and building materials covering large surface areas, including paper articles; metal articles; stone, plaster, cement, glass and ceramic articles	C204	Building/ construction materials not covered elsewhere
CC219	Machinery, mechanical appliances, electrical/electronic articles	C205	Electrical and electronic products
CC220	Other machinery, mechanical appliances,		
	electronic/electronic articles		
CC221	Construction and building materials covering large surface areas, including metal articles	C206	Metal products not covered elsewhere
CC222	Electrical batteries and accumulators	C207	Batteries
<u>Chemical Substances in Packaging, Paper, Plastic, Toys, Hobby Products</u>			
CC990	Non-TSCA use	C301	Food packaging
CC301	Packaging (excluding food packaging), including paper articles	C302	Paper products
CC302	Other articles with routine direct contact during normal use, including paper articles		
CC303	Packaging (excluding food packaging), including rubber articles; plastic articles (hard); plastic articles (soft)	C303	Plastic and rubber products not covered elsewhere
CC304	Other articles with routine direct contact during normal use including rubber articles; plastic articles (hard)		
CC305	Toys intended for children's use (and child dedicated articles), including fabrics, textiles, and apparel; or plastic articles (hard)	C304	Toys, playground, and sporting equipment
CC306	Adhesives applied at elevated temperatures	C305	

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.			
Column A: Section 8(a)(7) codes		**Column B: 2016 CDR codes**	
Code	**Category**	**Code**	**Category**
CC307	Cement/concrete		Arts, crafts, and hobby materials
CC308	Crafting glue		
CC309	Crafting paint (applied to body)		
CC310	Crafting paint (applied to craft)		
CC311	Fixatives and finishing spray coatings		
CC312	Modelling clay		
CC313	Correction fluid/tape	C306	Ink, toner, and colorant products
CC314	Inks in writing equipment (liquid)		
CC315	Inks used for stamps		
CC316	Toner/Printer cartridge		
CC317	Liquid photographic processing solutions	C307	Photographic supplies, film, and photochemicals
<u>Chemical Substances in Automotive, Fuel, Agriculture, Outdoor Use Products</u>			
CC401	Exterior car washes and soaps	C401	Automotive care products
CC402	Exterior car waxes, polishes, and coatings		
CC403	Interior car care		
CC404	Touch up auto paint		
CC405	Degreasers	C402	Lubricants and greases
CC406	Liquid lubricants and greases		
CC407	Paste lubricants and greases		
CC408	Spray lubricants and greases		
CC409	Anti-freeze liquids	C403	Anti-freeze and de-icing products
CC410	De-icing liquids		
CC411	De-icing solids		
CC412	Lock de-icers/releasers		
CC413	Cooking and heating fuels	C404	Fuels and related products
CC414	Fuel additives		
CC415	Vehicular or appliance fuels		
CC416	Explosive materials	C405	Explosive materials
CC417	Agricultural non-pesticidal products	C406	Agricultural products (non-pesticidal)

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.			
Column A: Section 8(a)(7) codes		**Column B: 2016 CDR codes**	
Code	**Category**	**Code**	**Category**
CC418	Lawn and garden care products	C407	Lawn and garden care products
Chemical Substances in Products not Described by Other Codes			
CC980	Other (specify)	C909	Other (specify)
CC990	Non-TSCA use	C980	Non-TSCA use

Table D-4Table D-4 provides the Function Category codes based on OECD harmonized codes to be used for section 8(a)(7) reporting, with corresponding Function Category codes from 2016 CDR reporting. The CDR codes are provided only as a reference to assist you if your company has used these codes in past reporting. Do not use CDR codes for section 8(a)(7) reporting.

Table D-4. Function Category Descriptions and Crosswalk: Section 8(a)(7) reporting and 2016-2020 CDR

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.			
Column A: Section 8(a)(7) codes		**Column B: 2016 CDR codes**	
Code	**Description**	**Code**	**Description**
F001	Abrasives	U001	Abrasives
F002	Etching agent		
F003	Adhesion/cohesion promoter	U002	Adhesives and Sealant Chemicals
F004	Binder		
F005	Flux agent		
F006	Sealant (barrier)		
F007	Absorbent	U003	Adsorbents and Absorbents
F008	Adsorbent		
F009	Dehydrating agent (desiccant)		
F010	Drier		
F011	Humectant		
F012	Soil amendments (fertilizers)	U004	Agricultural Chemicals (non-pesticidal)
F013	Anti-adhesive/cohesive	U005	Anti-Adhesive Agents
F014	Dusting agent		
F015	Bleaching agent	U006	Bleaching Agents
F016	Brightener		
F017	Anti-scaling agent	U007	Corrosion inhibitors and antiscaling agents
F018	Corrosion inhibitor		
F019	Dye	U008	Dyes
F020	Fixing agent (mordant)		
F021	Hardener	U009	Fillers
F022	Filler		
F023	Anti-static agent	U010	Finishing agents
F024	Softener and conditioner		

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.			
Column A: Section 8(a)(7) codes		**Column B: 2016 CDR codes**	
Code	**Description**	**Code**	**Description**
F025	Swelling agent		
F026	Tanning agents not otherwise specified		
F027	Waterproofing agent		
F028	Wrinkle resisting agent		
F029	Flame retardant	U011	Flame retardants
F030	Fuel agents	U012	Fuels and fuel additives
F031	Fuel		
F032	Heat transferring agent	U013	Functional fluids (closed systems)
F033	Hydraulic fluids		
F034	Insulators		
F035	Refrigerants		
F036	Anti-freeze agent	U014	Functional fluids (open systems)
F037	Intermediate	U015	Intermediates
F038	Monomers		
F039	Ion exchange agent	U016	Ion exchange agents
F040	Anti-slip agent	U017	Lubricants and lubricant additives
F041	Lubricating agent		
F042	Deodorizer	U018	Odor agents
F043	Fragrance		
F044	Oxidizing agent	U019	Oxidizing/reducing agents
F045	Reducing agent		
F046	Photosensitive agent	U020	Photosensitive chemicals
F047	Photosensitizers		
F048	Semiconductor and photovoltaic agent		
F049	UV stabilizer		
F050	Opacifer	U021	Pigments
F051	Pigment		
F052	Plasticizer	U022	Plasticizers
F053	Plating agent	U023	Plating agents and surface treating agents
F054	Catalyst	U024	Process regulators

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.			
Column A: Section 8(a)(7) codes		**Column B: 2016 CDR codes**	
Code	**Description**	**Code**	**Description**
F055	Chain transfer agent		
F056	Chemical reaction regulator		
F057	Crystal growth modifiers (nucleating agents)		
F058	Polymerization promoter		
F059	Terminator/Blocker		
F060	Processing aids, specific to petroleum production	U025	Processing aids, specific to petroleum production
F061	Antioxidant	U026	Processing aids, not otherwise listed
F062	Chelating agent		
F063	Defoamer		
F064	pH regulating agent		
F065	Processing aids not otherwise specified		
F066	Energy Releasers (explosives, motivepropellant)	U027	Propellants and blowing agents
F067	Foamant		
F068	Propellants, non-motive (blowing agents)		
F069	Cloud-point depressant	U028	Solids separation agents
F070	Flocculating agent		
F071	Flotation agent		
F072	Solids separation (precipitating) agent, not otherwise specified		
F073	Cleaning agent	U029	Solvents (for cleaning or degreasing)
F074	Diluent	U030	Solvents (which become part of product formulation or mixture)
F075	Solvent		
F076	Surfactant (surface active agent)	U031	Surface active agents
F077	Emulsifier		
F078	Thickening agent	U032	Viscosity adjustors
F079	Viscosity modifiers		
F080	Laboratory chemicals	U033	Laboratory chemicals
F081	Dispersing agent	U034	Paint additives and coating additives not described by other codes
F082	Freeze-thaw additive		
F083	Surface modifier		
F084	Wetting agent (non-aqueous)		

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.			
Column A: Section 8(a)(7) codes		**Column B: 2016 CDR codes**	
Code	**Description**	**Code**	**Description**
F085	Aerating and deaerating agents	U999	Other (specify)
F086	Explosion inhibitor		
F087	Fire extinguishing agent		
F088	Flavoring and nutrient		
F089	Anti-redeposition agent		
F090	Anti-stain agent		
F091	Anti-streaking agent		
F092	Conductive agent		
F093	Incandescent agent		
F094	Magnetic element		
F095	Anti-condensation agent		
F096	Coalescing agent		
F097	Film former		
F098	Demulsifier		
F099	Stabilizing agent		
F100	Alloys		
F101	Density modifier		
F102	Elasticizer		
F103	Flow promoter		
F104	Sizing agent		
F105	Solubility enhancer		
F106	Vapor pressure modifiers		
F107	Embalming agent		
F108	Heat stabilizer		
F109	Preservative		
F110	Anti-caking agent		
F111	Deflocculant		
F112	Dust suppressant		
F113	Impregnation agent		
F114	Leaching agent		
F115	Tracer		

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.			
Column A: Section 8(a)(7) codes		**Column B: 2016 CDR codes**	
Code	**Description**	**Code**	**Description**
F116	X-ray absorber		
F999	Other (specify)		
NOTE: For codes F085 – F116, no comparable crosswalk code existed in 2016 CDR			

Table D-5Table D-5 provides the Consumer and Commercial Product Category codes based on OECD harmonized codes to be used for section 8(a)(7) reporting, with corresponding consumer and commercial product category codes from 2016 CDR reporting. The CDR codes are provided only as a reference to assist you if your company has used these codes in past reporting. Do not use CDR codes for section 8(a)(7) reporting.

Table D-5. Consumer and Commercial Product Category Descriptions and Crosswalk

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
<u>Chemical Substances in Furnishing, Cleaning, Treatment Care Products</u>				
CC101	Construction and building materials covering large surface areas including stone, plaster, cement, glass and ceramicarticles; fabrics, textiles, and apparel	Cement flooring, stone tile, mirrors, flooring or wall materials, carpets, rugs, tapestries	C101	Floor coverings
CC102	Furniture & furnishings includingplastic articles (soft); leather articles	Foam armchair, couch/sofa, mattress(adult), mattress (infant), mattress (child), sleeping bag, beanbag chair	C102	Foam seating and bedding products
CC103	Furniture & furnishings including stone, plaster, cement, glass and ceramic articles; metal articles; or rubber articles	Tables, chairs, benches, outdoor furniture, or furniture feet	C103	Furniture and furnishings not covered elsewhere
CC104	Leather conditioner	Products applied to leather surfaces to preserve and/or restore strength, appearance, and flexibility.	C104	Fabric, textile, and leather products not covered elsewhere
CC105	Leather tanning, dye, finishing, impregnation and care products	Products applied to the surfaces of leather articles to impart desirable properties.		
CC106	Textile (fabric) dyes	Products applied to impart color(s) to textiles.		
CC107	Textile finishing and impregnating/surface treatment products	Products applied to the surfaces of textiles to impart water or stain resistances, flame resistance, but not dyes.		

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
CC108	All-purpose foam spray cleaner	Foams that are spray applied to surfaces such as countertops, tables, windows, and surfaces of appliances.	C105	Cleaning and furnishing care products
CC109	All-purpose liquid cleaner/polish	Liquids that are not spray applied and are applied to surfaces of furniture, silverware, sinks, tubs, carpeted floors, and hard-surface floors. Note: distinguish between “neat” and “dilute” products.		
CC110	All-purpose liquid spray cleaner	Liquids that are spray applied to surfaces such as countertops, tables, windows, and surfaces of appliances.		
CC111	All-purpose waxes and polishes	Waxes and other semi-solids that are not spray applied and are applied to the surfaces of furniture (generally wooden furniture) to improve shine and/or impart stain resistance.		
CC112	Appliance cleaners	Cleaners that are applied to the interior of appliances such as dishwashers, washing machines, electronic appliances, disposals, and ovens).		
CC113	Drain and toilet cleaners (liquid)	Liquids applied to toilets and/or drains that may remain in the sewer line for a time but ultimately go down the drain.		
CC114	Powder cleaners (floors)	Powders that are applied to carpets and rugs to clean or deodorize.		
CC115	Powder cleaners (porcelain)	Powders applied to sinks, showers, and tubs to remove dirt, soap scum, and mold.		

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
CC116	Dishwashing detergent (liquid/gel)	Liquid cleaners added to dishwashing machines to remove food residue from dishes.	C106	Laundry and dishwashing products
CC117	Dishwashing detergent (unit dose/granule)	Powder or powder/liquid tablet cleaners added to washing machines to remove dirt from clothing and other textiles.		
CC118	Dishwashing detergent liquid (hand-wash)	Liquid cleaners added to sinks and combined with water to remove food residue from dishes.		
CC119	Dry cleaning and associated products	Products used to remove dirt from clothing and other textiles in non- aqueous cleaning processes.		
CC120	Fabric enhancers	Products which enhance fabrics. Examples include liquid products added to washing machines or sheetsadded to driers, bleach, film, lime and rust removers.		
CC121	Laundry detergent (unit-dose/granule)	Powder or powder/liquid tablet cleaners added to washing machinesto remove dirt from clothing and other textiles.		
C122	Laundry detergent (liquid)	Liquid cleaners added to washing machines to remove dirt from clothing and other textiles.		
CC123	Stain removers	Applied to clothing before addition to laundry machine to remove stains (can be gels, liquids, or spray applications).		

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
CC124	Ion exchangers	Point of use filters which may be used by consumers in homes (e.g., refrigerator filters or pitcher filters) or in commercial and industrial settings to treat water for use in these processes.	C107	Water treatment products
CC125	Liquid water treatment products	Water treatment drops		
CC126	Solid/powder water treatment products	pH adjusters, filter media, water treatment tablets		
CC127	Liquid body soap	Liquid soap used for washing entire body.	C108	Personal care products
CC128	Liquid hand soap	Liquid soap used for washing hands.		
CC129	Solid bar soap	Solid soap used for washing hands and body.		
CC130	Air fresheners for motor vehicles	Aerosol spray and continuous action air products used to odorize or deodorize motor vehicles.	C109	Air care products
CC131	Continuous action air fresheners	Liquid, solid, gel diffuser, solid incense products and scented candle products that odorize or deodorize air in indoor environments.		
CC132	Instant action air fresheners	Aerosol spray and incense products that odorize or deodorize air in indoor environments.		
CC133	Anti-static spray	Spray applied to eliminate or reduce static electricity on apparel.	C110	Apparel and footwear care products
CC134	Apparel finishing, and impregnating/surface treatment products	Products applied to the surfaces of apparel to impart water or stain resistances, flame resistance, but not dyes.		

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
CC135	Insect repellent treatment	Product applied to clothing to repel insects.		
CC136	Pre-market waxes, stains, and polishes applied to footwear	Waxes, stains, and polishes applied to footwear to impart water resistance, improve appearance and impart other desirable properties.		
CC137	Post-market waxes, and polishes applied to footwear (shoe polish)	Waxes and polishes applied to footwear.		
CC138	Waterproofing and water-resistant sprays	Spray applied to impart water resistance to apparel or footwear.		
<u>Chemical Substances in Construction, Paint, Electrical, and Metal Products</u>				
CC201	Fillers and putties	Highly malleable materials used to repair, smooth over, or fill minor cracks and holes in building surfaces.	C201	Adhesives and sealants
CC202	Hot-melt adhesives	Adhesives (supplied in solid cylindrical sticks and intended for small applications) designed to be melted and dispensed through an electric hot glue gun.		
CC203	One-component caulks	Caulks (sealants) which are premixed with their final product formulation. Examples include acrylic solvent-based, butyl solvent- based, latex water-based, silicone and polyurethane.		
CC204	Solder	Metal alloys melted down to permanently bond metal parts together. Commonly used in electronics, plumbing and sheet metal work.		

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
CC205	Single-component glues and adhesives	Adhesives (packaged less than 8 ounces per bottle and intended for small amount per use applications such as bookbinding) which are premixed with their final product formulation. Product use and exposure to light, humidity, or temperature initiates chemical reaction and cure. Examples include anaerobic, cyanoacrylates, heat-cure, moisture-cure, radiation-cure, and silicones.		
CC206	Two-component caulks	Caulks (sealants) which are stored in two separate parts, generally a base and an activator. The activator is added to the base and mixed before application. Examples include epoxy-solvent based silicone and polyurethane.		
CC207	Two-component glues and adhesives	Adhesives (packaged in containers smaller than 8 ounces per container and intended for small applications) which are stored in two separate containers, generally a resin and a hardener which are then mixed together to initiate chemical reaction and cure. Examples include epoxies,		
		methyl methacrylates, silicon adhesives, and polyurethanes.		
CC208	Adhesive/caulk removers	Products applied to surfaces to unbind substances or remove sealants and to clean the underlying surface by softening adhesives, caulks and other glues so they can be removed.	C202	Paints and coatings

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
CC209	Aerosol spray paints	Pressurized one-component paint released with a propellant and spray applied as a fine mist.		
CC210	Lacquers, stains, varnishes and floor finishes	Liquids applied to surfaces such as floors, countertops, appliances, furnishings, decking, and patios to impart coloring or resistance to fade, scuffing, marking, or wear.		
CC211	Paint strippers/removers	Liquid product applied to surfaces to remove paint, coatings and other finishes and also to clean the underlying surface.		
CC212	Powder coatings	Dry powder coating that does not contain solvents and is cured under heat to create a coating film.		
CC213	Radiation curable coatings	Coatings designed to cure onto surface when exposed to radiation such as ultraviolet or electron beam radiation.		
CC214	Solvent-based paint	Paints that have been formulated to have a solvent as the vehicle.		
CC215	Thinners	Liquids to dilute paints and coatings to obtain suitable viscosity for paint application.		
CC216	Water-based paint	Paints that have been formulated to have water as the main vehicle.		
CC217	Construction and building materials covering large surface areas, including wood articles	Floor decking, claddings, toys outdoor equipment, walls, flooring	C203	Building/ construction materials - wood and engineered wood products

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
CC218	Construction and building materials covering large surface areas, including paper articles; metal articles; stone, plaster, cement, glass and ceramic articles	Construction and building materials; e.g. insulation panels, wall papers, roof sheets, drinking water pipes, sewer pipes, cement flooring, mirrors	C204	Building/ construction materials not covered elsewhere
CC219	Machinery, mechanical appliances, electrical/electronic articles	Refrigerators, washing machines, vacuum cleaners, computers, telephones, drills, saws, smoke detectors, thermostats, radiators	C205	Electrical and electronic products
CC220	Other machinery, mechanical appliances, electronic/electronic articles	Large-scale stationary industrial tools		
CC221	Construction and building materials covering large surface areas, including metal articles	Roof sheets, drinking water pipes, sewer pipes	C206	Metal products not covered elsewhere
CC222	Electrical batteries and accumulators	Batteries	C207	Batteries
<u>Chemical Substances in Packaging, Paper, Plastic, Toys, Hobby Products</u>				
CC990	Non-TSCA use	Items included under non-TSCA use include food contact articles, such as plastic wrap, plastic dinner ware, food storage, packaging containers.	C301	Food packaging
CC301	Packaging (excluding food packaging), including paper articles	Paper packaging	C302	Paper products
CC302	Other articles with routine direct contact during normal use, including paper articles	Nappies, feminine hygiene products, adult incontinence products, tissues, towels, toilet paper, newspapers, books, magazines, photographic paper and negatives		

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
CC303	Packaging (excluding food packaging), including rubber articles; plastic articles (hard); plastic articles (soft)	Phone covers, personal tablet covers, styrofoam packaging, bubble wrap	C303	Plastic and rubber products not covered elsewhere
CC304	Other articles with routine direct contact during normal use including rubber articles; plastic articles (hard)	Gloves, boots, clothing, rubber handles, gear lever, steering wheels, handles, pencils, handheld device casing		
CC305	Toys intended for children's use (and child dedicated articles), including fabrics, textiles, and apparel; or plastic articles (hard)	Stuffed toys, blankets, comfort objects, dolls, car, animals, teething rings	C304	Toys, playground, and sporting equipment
CC306	Adhesives applied at elevated temperatures	Used at elevated temperatures to melt and apply adhesive which when cooled, hardens and adheres the two substances to one another. Examples include solder and hot-melt adhesive, see adhesive definitions.	C305	Arts, crafts, and hobby materials
CC307	Cement/concrete	Used to create and support structures and pathways.		
CC308	Crafting glue	Used to adhere two substances to one another, see adhesives definitions.		
CC309	Crafting paint (applied to body)	Used to add color to fingers, faces, or other body parts.		
CC310	Crafting paint (applied to craft)	Used to add color to crafting substances, see paints definitions.		
CC311	Fixatives and finishing spray coatings	Fixatives, shellacs, or other spray applied coatings intended to cover or hold other arts and crafts materials to a surface.		
CC312	Modelling clay	Used to mold or sculpt.		

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
CC313	Correction fluid/tape	Fluids used to cover up permanent ink so that corrections can be made.	C306	Ink, toner, and colorant products
CC314	Inks in writing equipment (liquid)	Liquids used in pens, markers, or other writing instruments.		
CC315	Inks used for stamps	Inks incorporated into stamp or ink pads used to apply ink to paper and other substrates.		
CC316	Toner/printer cartridge	Pigmented liquids, toners or powders contained in cartridges, bottles, or other dispensers used in printers and copy machines. This category includes printing inks for commercial applications.		
CC317	Liquid photographic processing solutions	Chemicals used in the stop bath, fixing bath, hardener, or stabilizer to develop photographs.	C307	Photographic supplies, film, and photochemicals
Chemical Substances in Automotive, Fuel, Agriculture, Outdoor Use Products				
CC401	Exterior car washes and soaps	Cleaning agents used to remove dirt and grime.	C401	Automotive care products
CC402	Exterior car waxes, polishes, and coatings	Used to increase the shine, add UV protection and scratch resistance to automotive paints, or provide waterproofing/resistant properties to windshields and automotive window glass.		
CC403	Interior car care	Cleaning agents used to remove stains from interior carpets and textiles, rubber, vinyl, or plastic.		
CC404	Touch up auto paint	Used to paint over scratches or cover up dent marks on automotive paints.		
CC405	Degreasers	Product that remove greases or oils from hard surfaces, machinery, or tools.	C402	Lubricants and greases

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
CC406	Liquid lubricants and greases	Liquids that reduce friction, heat generation and wear between surfaces.		
CC407	Paste lubricants and greases	Pastes that reduce friction, heat generation and wear between surfaces.		
CC408	Spray lubricants and greases	Sprays that reduce friction, heat generation and wear between surfaces.		
CC409	Anti-freeze liquids	Reduce the freezing point of surfaces.	C403	Anti-freeze and de-icing products
CC410	De-icing liquids	Reduce the freezing point of surfaces in order to remove ice.		
CC411	De-icing solids	Ice melting crystals, rock salts		
CC412	Lock de-icers/releasers	Applied within locks to remove ice so that doors can be opened.		
CC413	Cooking and heating fuels	Pressurized liquid fuels generally contained within metal containers and released directly into an appliance in a controlled way to prevent direct release.	C404	Fuels and related products
CC414	Fuel additives	Added to fuels to improve properties such as stability, corrosion, oxygenation, and octane rating.		
CC415	Vehicular or appliance fuels	Liquid fuels stored in containers and refilled into vehicles or appliances as needed.		
CC416	Explosive materials	Chemical substances capable of producing a sudden expansion usually accompanied by the production of heat and large changes in pressure upon initiation, that are intended for consumer or commercial use. Examples include pyrotechnics,	C405	Explosive materials

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
		high explosives and propellants, igniter, primer, initiatory, illuminants, smoke and decoy flares, and incendiaries.		
CC417	Agricultural non-pesticidal products	Products used to increase the productivity of crops, or aid in the harvesting of crops. Examples include fertilizers, colorants, and application aids, and soil amendments (e.g. products added to soil to adjust pH, retain water or alter other properties).	C406	Agricultural products (non-pesticidal)
CC418	Lawn and garden care products	Chemical substances contained in lawn, garden, outdoor or potted plant, and tree care products that are intended for consumer or commercial use should be reported under this code. Examples of lawn and garden care products include fertilizers and nutrient mixtures, soil amendments, mulches, pH adjustors, water retention beads, vermiculite, and perlite. Excludes any substance that is manufactured, processed, or distributed in commerce for use as a pesticide as defined in the Federal Insecticide, Fungicide, and Rodenticide Act.	C407	Lawn and garden care products
Chemical Substances in Products not Described by Other Codes				
CC980	Other (specify)	Provide description of use.	C909	Other (specify)
CC990	Non-TSCA use	Chemical substances contained in products intended for consumer or commercial use that are not regulated by TSCA should be reported under this code. Examples of products with non-TSCA uses include	C980	Non-TSCA use

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: Section 8(a)(7) codes			**Column B: 2016 CDR codes**	
Code	**Name**	**Description**	**Code**	**Name**
		pesticide, insecticide, rodenticide and fungicide formulations; food or drink for humans or animals; articles intended for use in the diagnosis, cure, mitigation, treatment, or prevention of disease in humans or animals; substances intended to be applied to the human body other than soap; any radioactive source material, special nuclear material, or byproduct material; pistols, revolvers, fire arms, or ammunition; and tobacco or tobacco products.		

Table D-6Table D-6 provides examples of products intended for use by children, including 2020 CDR (OECD-based) codes to be used for section 8(a)(7) reporting as well as 2016 CDR codes. This table is meant to help you identify products intended for use by children and may not include all products intended for use by children. The 2016 CDR codes in this table are provided only as a reference to assist you if your company has used these codes in past reporting. Do not use 2016 CDR codes for section 8(a)(7) reporting.

Table D-6. Examples of Products Intended for Use by Children

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: section 8(a)(7) codes		**Column B: 2016 CDR codes**		**Examples**
Codes	**Category**	**Code**	**Category**	
Chemical Substances in Furnishings, Cleanings, Treatment Care Products				
CC102	Furniture & furnishings including Plastic articles (soft); Leather articles	C102	Foam seating and bedding products	Child's car seat, children's sheets
CC103	Furniture & furnishings including Stone, plaster, cement, glass and ceramic articles; Metal articles; or Rubber articles	C103	Furniture and furnishings not covered elsewhere	Baby cribs, changing tables
CC106	Textile (fabric) dyes	C104	Fabric, textile, and leather products not covered elsewhere	Children's clothing
CC107	Textile finishing and impregnating/surface treatment products			Children's clothing, children's sheets, child's car seat
CC127	Liquid body soap	C108	Personal care products	Baby shampoo, children's bubble bath
Chemical Substances in Construction, Paint, Electrical and Metal Products				
CC219	Machinery, mechanical appliances, electrical/electronic articles	C205	Electrical and electronic products	Electronic games, remote control cars
CC222	Electrical batteries and accumulators	C207	Batteries	Batteries used in toys
Chemical Substances in Packaging, Paper, Plastic, Hobby Products				
CC302	Other articles with routine direct contact during normal use, including paper articles	C302	Paper products	Diapers, baby wipes, coloring books

Use column A for all reporting. Column B shows 2016 CDR codes, which may have been used for CDR reporting.				
Column A: section 8(a)(7) codes		**Column B: 2016 CDR codes**		**Examples**
Codes	**Category**	**Code**	**Category**	
CC305	Toys intended for children's use (and child dedicated articles), including Fabrics, textiles, and apparel; or Plastic articles (hard)	C304	Toys, playground, and sporting equipment	Pacifiers, toy trucks, dolls, toy cars, wagons, action figures, balls, swing sets, slides, skates, baseball gloves, kid's rake
CC306	Adhesives applied at elevated temperatures	C305	Arts, crafts, and hobby materials	Craft glue for a hot glue gun
CC308	Crafting glue			Craft glue
CC309	Crafting Paint (applied to body)			Chemicals used to add color to body paint, finger paints

Testimony of James C. Kenney
Cabinet Secretary
New Mexico Environment Department

To the United States Senate
Committee on Environment and Public Works

Regarding a hearing on
“Examining PFAS as a Hazardous Substance”
Wednesday, March 20, 2024
10 am EDT

NMOGA Exhibit D8

PFAS and Federal Laws

Mr. Chairman, Ranking Member Capito, members of the Committee, my name is James Kenney and I currently serve as the Secretary of the New Mexico Environment Department (NMED) in Governor Michelle Lujan Grisham's Cabinet. I appreciate the opportunity to provide testimony today on behalf of the State of New Mexico and its citizens regarding the impacts of PFAS. My testimony draws on my nearly 28 years of experience in implementing public health and environmental regulatory and enforcement programs at the state and federal levels.

The mission of the NMED is to protect and restore the environment and to foster a healthy and prosperous New Mexico for present and future generations. NMED successfully implements federal and state programs related to air and water quality, drinking water and food safety, solid and hazardous waste, occupational health and safety, and other such programs. We keep New Mexicans healthy and safe, working to prevent acute and chronic exposures to biological, chemical, and radiological agents.

As a group of chemicals, the broad family of chemical compounds commonly referred to as PFAS or forever chemicals are unlike any other class of environmental pollutants for the following reasons:

- These chemicals are found in both consumer goods and industrial applications and are entering our homes, businesses, manufacturing facilities, and environment.

- Once in the environment, these chemicals are persistent – meaning they do not naturally decompose into less harmful chemicals.

- Instead, these chemicals remain in our environment and accumulate in people and wildlife, as well as our land and water.

- And we conclusively know that exposure to these chemicals has been associated with cancer, diabetes, liver damage, high cholesterol, obesity, thyroid disease, asthma, immune system dysfunction, reduced fertility, low birth weight, and effects on children's cognitive and neurobehavioral development.[1]

With PFAS moving through our economy, additional legislation to protect consumers from PFAS where they live, work, and play is warranted. When it comes to protecting human health and the environment from current and future release of PFAS, Congress has already established laws with broad authority to address this pollution. Some of these statutes include the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA).

---

[1] https://www.epw.senate.gov/public/_cache/files/2/2/22ca7c4b-b1dc-4a12-9264-7a4f16608933/BF2D70A4FB747A3F61E584CC30D58D0A.birnbaum-testimony-03.28.2019.pdf

Commonsense Frameworks for the Clean-Up of Hazardous Substances

CERCLA

Congress enacted CERCLA in response to public health and environmental impacts related to industrial pollution in the 1970s. Yet, one of the largest and most recalcitrant PFAS polluters in the United States in the U.S. Department of Defense (U.S. DOD).

Until Congress restores the sole jurisdiction for the implementation of abatement and settlement authorities to the U.S. Environmental Protection Agency (U.S. EPA), CERCLA action to address PFAS pollution is holding the wrong polluter accountable.

In 1987, Executive Order (EO) 12580 was executed to broadly implement CERCLA across multiple federal agencies. In 1996, EO 13016 further modified EO 12580 to delegate abatement and settlement authorities to the Secretary of Defense with the concurrence of the U.S. EPA Administrator.[2] Effectively, EO 12580 and EE 13016 were codified into federal law at 10 U.S. Code §§ 2700-2711, commonly referred to as the Defense Environmental Restoration Program.

Effectively, the U.S. DOD – one of the largest and most prolific PFAS polluters in the United States – is fully in charge of its own PFAS clean-up. This has resulted in inconsistent implementation across the United States.

Related to CERCLA, New Mexico supports the U.S. EPA's proposed rulemaking to require the reporting of certain PFAS released into the environment that meet or exceed reportable quantities to local emergency responders.

Using discretion to hold the primary polluter accountable in New Mexico, the U.S. EPA's proposed designation of certain PFAS as CERCLA hazardous substances will allow states to pursue Natural Resource Damage claims. For sites contaminated with hazardous substances, CERCLA not only mandates cleanup to protect human health and the environment but also gives designated federal and state agencies and tribes the authority to recover, on behalf of the public, all costs to restore or replace injured natural resources to the conditions in which they existed without the hazardous substance release.[3] The designation of such chemicals as hazardous substances is thus essential to the state's ability to recover damages under CERCLA to compensate the people of New Mexico for losses resulting from injury to natural resources caused by PFAS.

RCRA

Congress enacted RCRA in 1976 in response to "a rising tide of scrap, discarded, and waste materials" that had become a matter of national concern. In enacting RCRA, Congress declared it a national policy "that, wherever feasible, the generation of hazardous waste is to be reduced or eliminated as expeditiously as possible. Waste that is nevertheless generated should be treated,

---

[2] https://www.archives.gov/federal-register/codification/executive-order/12580.html

[3] CERCLA §107(f)(1), CERCLA 107(a)(4(C), under "Liability for NRD and Judicial Review."

stored, or disposed of to minimize the present and future threat to human health and the environment." Congress recognized, however, that "the collection of and disposal of solid wastes should continue to be primarily the function of State, regional, and local agencies. …" Thus, RCRA allows any state to administer and enforce a hazardous waste program subject to authorization from the U.S. EPA.[4]

In June 2021, the Governor Michelle Lujan Grisham petitioned the U.S. EPA to list PFAS, either individually or as a class, as a hazardous waste under RCRA.[5] In taking this bold step, New Mexico affirmed its legal authority under RCRA to address PFAS pollution. New Mexico's petition incorporated two earlier petitions submitted to U.S. EPA by reference, which also requested the U.S. EPA to regulate PFAS under RCRA. These petitions included a January 15, 2020 request by the Environmental Law Clinic at UC Berkeley and a September 19, 2019 by the Public Employees for Environmental Responsibility.[6,7]

In October 2021, the U.S. EPA acted upon Governor Michelle Lujan Grisham's petition.[8] The U.S. EPA indicated in the letter that it would initiate a rulemaking process to propose adding PFOA, PFOS, PFBS and GenX (Hexafluoropropylene oxide-dimer acid) as RCRA hazardous constituents under RCRA corrective action. The U.S. EPA also stated that listing as a hazardous constituent was a building block for any future work to regulate PFAS as a RCRA listed hazardous waste.[9]

RCRA presents a common-sense approach to managing discarded PFAS in New Mexico and across all states and territories. Currently, 50 states and territories have been granted authority to implement RCRA (in part or in whole) in lieu of the U.S. EPA. The U.S. EPA ensures national consistency while providing flexibility to states to implement rules. State RCRA programs must be at least as stringent as the federal requirements, but states can adopt more stringent requirements as well. Unlike CERCLA, the U.S. EPA and 50 states and territories implement RCRA – not the U.S. DOD or any other federal agency.

---

[4] The EPA authorized New Mexico's state program pursuant to RCRA in 1985, 40 C.F.R. § 272.1601(a), and delegated to New Mexico "primary responsibility for enforcing its hazardous.
waste management program." 40 C.F.R. § 272.1601(b). New Mexico's Hazardous Waste Act and regulations promulgated pursuant to it are incorporated by reference into RCRA.

[5] https://www.epa.gov/system/files/documents/2021-10/508compliant_ezd5442262_2021-06-23-governor-letter-to-epa-for-pfas-petition.pdf-incoming-document.pdf

[6] https://www.epa.gov/sites/production/files/2020-04/documents/pfas_petition_for_haz_waste_jan_2020_metadata_added.pdf

[7] https://www.epa.gov/sites/production/files/2020-04/documents/peer_pfas_rulemaking_petition_metadata_added.pdf

[8] https://www.epa.gov/system/files/documents/2021-10/oct_2021_response_to_nm_governor_pfas_petition_corrected.pdf

[9] https://www.epa.gov/hw/proposal-list-nine-and-polyfluoroalkyl-compounds-resource-conservation-and-recovery-act#Summary

The United States Sues New Mexico to Stop State Action

In December 2018, the NMED issued a hazardous waste facility permit to Cannon Air Force Base under its RCRA-authorized hazardous waste authorities exercising State authority requiring Cannon Air Force Base to address PFAS contamination. The permit, among other things, imposed RCRA corrective action requirements for PFAS at the facility. Initially, Cannon Air Force Base did not contest the inclusion of PFAS in the permit.

In January 2019 without any warning, the U.S. Department of Justice (U.S. DOJ), on behalf of the U.S. Air Force, challenged the permit in the Federal District Court for the District of New Mexico. In the complaint, the U.S. DOJ took the position that New Mexico's corrective action regulation – which mirrors the federal regulation – does not authorize corrective action for substances that are not listed or characteristic hazardous wastes under the State's regulations, even if they might be hazardous under the broader statutory definition.

On June 1, 2021, the U.S. DOJ filed a memorandum defending its position that the NMED acted arbitrarily and capriciously when it issued a permit requiring the U.S. Air Force to clean up its PFAS contamination at Cannon Air Force Base that resulted from decades of releases of PFAS containing firefighting foams known as aqueous film forming foams (AFFF) under the State's Hazardous Waste Act as it relates to the implementation of RCRA.

For the past five years, the U.S. DOJ and the U.S. DOD have appeared more interested in fighting New Mexico than fighting PFAS pollution – attempting to affirm its CERCLA autonomy and conflict of interest as polluter and watchdog. The U.S. DOJ and U.S. DOD are seeking to undermine Congressional intent, the U.S. EPA, and NMED's implementation of RCRA.

Yet the U.S. DOD has been inconsistent in implementing CERCLA and its own Defense Environmental Restoration Program. On July 30, 2020, the U.S. Air Force announced it began investigative field work around the former Reese Air Force Base, near Lubbock, Texas, related to PFAS contamination. The U.S. Air Force stated: "These investigations are part of the PFAS Affected Property Assessment investigation, required by the Resource Conservation and Recovery Act (RCRA) Permit and Compliance Plan issued to the Air Force by the Texas Commission on Environmental Quality."[10] Clearly, the U.S. Air Force agrees PFAS contamination is subject to RCRA corrective action in Texas. Contrast this cooperative relationship with Texas to the federal lawsuit that has cost New Mexicans over $8 million in taxpayer dollars spent in defensive litigation and to perform the work that the U.S. DOD has failed to perform in New Mexico. Ironically, the U.S. DOJ has alleged that NMED has acted arbitrarily and capriciously when it issued a permit requiring the U.S. Air Force to clean up its PFAS contamination at Cannon Air Force Base.

---

[10] https://www.af.mil/News/Article-Display/Article/2295836/air-force-begins-field-work-to-investigate-pfas-at-former-reese-afb/

In June 2021, the Governor Michelle Lujan Grisham petitioned the U.S. EPA to list PFAS, either individually or as a class, as a hazardous waste under RCRA.[11] The Governor's petition illustrated the our commitment to meaningfully protect the 50,000 nearby residents of Curry and Roosevelt Counties from the further migration of PFAS contamination from Cannon Air Force Base through groundwater which serves as the primary source of drinking water for these communities.

New Mexico's petition incorporated two earlier petitions submitted to U.S. EPA by reference, which also requested the U.S. EPA to regulate PFAS under RCRA. The U.S. EPA acted upon the Governor of New Mexico's petition with a letter in October 2021.[12] The U.S. EPA indicated in the letter that it would initiate a rulemaking process to propose adding PFOA, PFOS, PFBS and GenX (Hexafluoropropylene oxide-dimer acid) as RCRA hazardous constituents. A listing as a hazardous constituent is a building block for any future work to regulate PFAS as a RCRA listed hazardous waste.[13]

On February 1, 2024, the U.S. EPA proposed rules related to New Mexico's petition and expect to finalize these rules this year. However, Congress could take decisive action to list PFAS as a hazardous substance or even as hazardous waste. In doing so, Congressional action would immediately provide critical public health and environmental protections while saving the U.S. EPA both time and resources. States and territories could then implement RCRA with the assistance of the U.S. EPA by focusing efforts to address the primary sources of PFAS pollution.

Impacts to our Health, Environment and Economy

PFAS threaten our health, environment, and economy. While the U.S. EPA's focus on a national drinking water standard is paramount, these chemicals continue to find their way into our lives through a variety of pathways.

From a consumer standpoint, water or stain resistant sprays containing PFAS are offered to customers by some retailers who sell furniture, rugs, and textiles. When these household goods are purchased, retailers offer and apply water- or stain-resistant sprays containing PFAS. Often, the water- or stain-resistant application takes place at a retail store or local warehouse prior to the consumer picking up their purchase. The retailer applies the spray to the household product, cleans up any waste, and disposes of any waste generated from the process. The use of these chemicals by retailers is largely unregulated and may present a risk to consumers, employees, municipal wastewater treatment facilities, and solid waste management facilities. Ultimately, the consumer may not be aware that their stain- or water-resistant furniture, rug or textile may contain PFAS chemicals. This area needs greater study, disclosure and possibly regulation to prevent human and wildlife exposure to PFAS.

---

[11] https://www.epa.gov/system/files/documents/2021-10/508compliant_ezd5442262_2021-06-23-governor-letter-to-epa-for-pfas-petition.pdf-incoming-document.pdf

[12] https://www.epa.gov/system/files/documents/2021-10/oct_2021_response_to_nm_governor_pfas_petition_corrected.pdf

[13] https://www.epa.gov/hw/proposal-list-nine-and-polyfluoroalkyl-compounds-resource-conservation-and-recovery-act#Summary

From an economic standpoint, agriculture is part of New Mexico's cultural and economic identity. We are the top state in the country in chile production, second in pecans, in the top 10 in milk production and have the largest dairy herd size in the nation. According to the most recent U.S. Census of Agriculture, there are 20,900 farms in the state and agriculture and food products are among the state's top five exports. The agricultural industry employs over 23,000 people in the state with cash receipts approaching $3.7 billion annually.

In October of 2018, a Curry County, New Mexico dairy farmer that neighbors Cannon Air Force Base learned his water was contaminated with PFAS. The milk was tested, and the New Mexico Department of Agriculture worked with the U.S. Food and Drug Administration (FDA) to obtain an advisory level of contamination. The milk was immediately pulled off sale. Since then, the dairy farmer dumped tens of millions of gallons of milk, losing millions of dollars in revenue that otherwise would have recirculated in our state and national economy. In May of 2022, the fifth-generation dairy farmer was forced to euthanize his entire herd of 3,665 cows because of PFAS contamination. NMED provided over $850,000 to the dairy farmer for expenses associated with the proper disposal of PFAS-contaminated hazardous carcasses.

New Mexico's agricultural reputation is essential to the nation's milk supply and our state economy. Other farms near Cannon Air Force Base could face a similar fate. Given that Curry County is one of the nation's top milk producers and home to North America's largest and most technologically advanced cheddar cheese plants in the world, New Mexico continues to safeguard its agricultural products from PFAS contamination through prevention and analytical testing in the absence of clear national standards from the U.S. FDA.

Also essential to New Mexico's economy is tourism. The New Mexico Tourism Department reports that the state has a high percentage of out-of-state visitors who come to New Mexico for outdoor recreation activities, such as river rafting, fly fishing, camping, boating, and wildlife viewing along the State's scenic waters. In fact, outdoor recreation accounted for 1.9 percent of New Mexico's gross domestic product and created $2.4 billion in added value for New Mexico and created almost 28,000 jobs.

As an example of how PFAS contamination could impact both tourism and human health, exceedingly high levels of PFAS were detected in Lake Holloman in Otero County, New Mexico, home of Holloman Air Force Base, where PFAS was released into the environment through decades of the U.S. Air Force's use of AFFF. Lake Holloman is considered an important habitat for birds, including migrating ducks, shorebirds, and a number of federally listed endangered species and state-listed species of concern. Lake Holloman also serves as a valuable recreational resource to the community surrounding the base, as it is used for boating, bird watching, and camping. In 2019, the New Mexico Attorney General requested the U.S. Air Force close Lake Holloman, and the New Mexico Department of Health directed the public to avoid all contact with the water in Lake Holloman, including drinking or swimming.[14,15] In 2023, A University of New Mexico (UNM) study found extremely high levels of PFAS contamination in nearly two dozen bird and mammal species around Lake Holloman. Researchers at UNM have found that the ducks at Holloman Air Force Base were extraordinarily contaminated – to the

---

[14] https://www.env.nm.gov/wp-content/uploads/sites/21/2019/10/PI-Motion.pdf

[15] https://www.nmhealth.org/news/information/2019/5/?view=764

point where humans should not consume them at all. Lake Holloman is adjacent to White Sands National Park, which is the most visited National Park in New Mexico, welcoming almost 730,000 visitors in 2023.

Impacts to tourism hurt yet another New Mexico economic sector: outdoor recreation. Outdoor recreation is among New Mexico's largest economic sectors, representing the lifeblood of communities across the state and providing livelihoods for tens of thousands of New Mexicans. More than twice as many jobs in New Mexico depend on outdoor recreation than on the energy and mining sectors combined. The nationally leading New Mexico Outdoor Recreation Division, created through legislation in 2019, is tasked with increasing outdoor recreation-based economic development, tourism and ecotourism; recruiting new outdoor recreation business to New Mexico; and promoting education about outdoor recreation's benefits to public health.

We have already seen how environmental contamination can devastate livelihoods: New Mexico's agriculture, tourism and outdoor recreation economies suffered greatly after the 2015 Gold King Mine blowout. As a result of the blowout in southwest Colorado, more than three million gallons of bright yellow mine water contaminated with heavy metals flowed into Cement Creek, a tributary of the Animas River. The toxic plume flowed into New Mexico and the San Juan River, which also runs through the Navajo Nation and Utah.

The spill led to costs incurred by the state, local municipalities, and tribal nations to clean up the contamination. The spill also caused pollution in agricultural areas and adversely impacted New Mexicans in the agricultural, tourism and outdoor recreation industries in the northwest corner of the state. Although extensive testing indicates that water used to irrigate crops in the Animas Valley is now safe and well within irrigation standards, farmers continue to see lower sales due to the stigma left behind by the catastrophic release.

And PFAS contamination continues to grow in New Mexico with numerous active and closed federal facilities, including the New Mexico National Guard facilities in Rio Rancho, Roswell, and Santa Fe; the Department of Energy facilities in Albuquerque and Los Alamos; and other U.S. DOD facilities across the state.

The absence of federal PFAS standards and definitive action under RCRA and other federal environmental laws threatens our communities, consumers, workforce, tourists, and economy and shifts a huge burden to states and tribes from coast to coast. New Mexico will continue to push for a whole-of-government approach from the federal government, in close coordination with states and tribes, with the requisite sense of urgency that these pervasive and persistent contaminants demand.

Conclusion

To protect public health and the environment, Congress should take the following steps:

1. Modify CERCLA and the Defense Environmental Restoration Program so the U.S. EPA is solely responsible for the implementation of CERCLA.

2. Take immediate action to list discarded PFAS as a RCRA hazardous waste.

3. Increase and direct funding to U.S. EPA-authorized state RCRA programs to manage PFAS-related responsibilities.

Prepared in cooperation with the New Mexico Environment Department

Assessment of Per- and Polyfluoroalkyl Substances in Water Resources of New Mexico, 2020–21

Scientific Investigations Report 2023–5129
Version 1.2, April 2024

U.S. Department of the Interior
U.S. Geological Survey

NMOGA Exhibit D9

Cover.

Top left: Kimberly Beisner sampling the Animas River at Farmington, New Mexico. Photograph by Erik Storms, U.S. Geological Survey (USGS).

Top right: Elaiya Jurney sampling the Rio Grande above Buckman Diversion, near White Rock, N. Mex. Photograph by Rebecca Travis, USGS.

Bottom left: Christina Ferguson sampling a well in Curry County, N. Mex. Photograph by Joseph Beman, USGS.

Bottom right: Kimberly Beisner sampling a well in Albuquerque, N. Mex., for per- and polyfluoralkyl substances. Photograph by Natalia Montero, USGS.

Assessment of Per- and Polyfluoroalkyl Substances in Water Resources of New Mexico, 2020–21

By Rebecca E. Travis, Kimberly R. Beisner, Kate L. Wilkins, Jeramy R. Jasmann, Steffanie H. Keefe, and Larry B. Barber

Prepared in cooperation with the New Mexico Environment Department

Scientific Investigations Report 2023–5129
Version 1.2, April 2024

U.S. Department of the Interior
U.S. Geological Survey

U.S. Geological Survey, Reston, Virginia: 2024
First release: January 2024
Revised: March 2024 (ver. 1.1), online
Revised: April 2024 (ver 1.2), online

Suggested citation:
Travis, R.E., Beisner, K.R., Wilkins, K.L., Jasmann, J.R., Keefe, S.H., and Barber, L.B., 2024, Assessment of per- and polyfluoroalkyl substances in water resources of New Mexico, 2020–21 (ver. 1.2, April 2024): U.S. Geological Survey Scientific Investigations Report 2023–5129, 98 p., https://doi.org/10.3133/sir20235129.

Associated data for this publication:
U.S. Geological Survey, 2022, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, https://doi.org/10.5066/F7P55KJN.

ISSN 2328-0328 (online)

Acknowledgments

The authors would like to thank the New Mexico Environment Department, in particular Jill Turner, Lena Schlichting, and Andy Jochems, for their assistance and support of this project. Additional thanks to the numerous private entities who allowed U.S. Geological Survey (USGS) to sample at their facilities across the State of New Mexico.

The authors would like to acknowledge those who helped collect and analyze samples during the COVID-19 pandemic and its associated challenges. USGS staff at the USGS Integrated Water Chemistry Assessment Laboratory, including David Roth and Paul Bliznik, are much appreciated for their dedication to making multiple analyses and assuring high data quality. Many additional thanks to the numerous staff at the USGS who participated in the collection of these samples, including Robert Henrion, Joseph Beman, Edyth Hermosillo, Alanna Jornigan, Elaiya Jurney, Natalia Montero, Harold Nelson, Brittany Mora, Heather Cornell, Steve Hannes, Rachel Mixon, and Scott Green.

Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Velocity	
foot per second (ft/s)	0.3048	meter per second (m/s)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
	Flux	
gram per day	0.03527	ounce per day

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$°F = (1.8 \times °C) + 32$.

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L), micrograms per liter (µg/L), or nanograms per liter (ng/L).

Activities for radioactive constituents in water are given in picocuries per liter (pCi/L).

Results for measurements of stable isotopes of an element (with symbol E) in water, solids, and dissolved constituents commonly are expressed as the relative difference in the ratio of the number of the less abundant isotope (iE) to the number of the more abundant isotope of a sample with respect to a measurement standard.

Abbreviations

DEET	N,N-diethyl-meta-toluamide
DOC	dissolved organic carbon
EPA	U.S. Environmental Protection Agency
MCL	maximum contaminant level
MRI	magnetic resonance imaging
NMDS	nonmetric multidimensional scaling
NMED	New Mexico Environment Department
NPDES	National Pollutant Discharge Elimination System
PFAS	per- and polyfluoroalkyl substances
PFBA	perfluorobutanoic acid
PFBS	perfluorobutanesulfonic acid
PFDA	perfluorodecanoic acid
PFHpA	perfluoroheptanoic acid
PFHxA	perfluorohexanoic acid
PFHxS	perfluorohexanesulfonic acid
PFNA	perfluorononanoic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonic acid
PFOSA	perfluorooctane sulfonamide
PFPeA	perfluoropentanoic acid
PFPeS	perfluoropentanesulfonic acid
pmc	percent modern carbon
REE	rare earth element
RPD	relative percent difference
SD	standard deviation
SMCL	secondary maximum contaminant level
SRL	study reporting level
TDS	total dissolved solids
USGS	U.S. Geological Survey
WWTP	wastewater treatment plant

Assessment of Per- and Polyfluoroalkyl Substances in Water Resources of New Mexico, 2020–21

By Rebecca E. Travis, Kimberly R. Beisner, Kate L. Wilkins, Jeramy R. Jasmann, Steffanie H. Keefe, and Larry B. Barber

Abstract

Per- and polyfluoroalkyl substances (PFAS) have been detected in public and private drinking-water wells, springs, and surface waters in New Mexico; however, the presence and distribution of PFAS in water resources across the State are not well characterized. From August 2020 to October 2021, the U.S. Geological Survey, in cooperation with the New Mexico Environment Department, collected water-quality samples from groundwater and surface-water sites throughout New Mexico. One hundred and seventeen groundwater wells were sampled from unconfined water-table aquifers for PFAS and a geochemical suite including major ions, trace elements, nutrients, dissolved organic carbon (DOC), stable isotopes of oxygen and hydrogen, tritium, and carbon-14 to provide context for groundwater age and geochemical evolution. Eighteen surface-water samples were analyzed for PFAS, and select samples were analyzed for wastewater tracers, major ions, trace elements, and DOC. Blanks and replicates indicated low bias and variability for PFAS, wastewater tracers, and geochemical compounds.

Twenty-seven of the 117 groundwater sites had PFAS concentrations reported above the detection level, and there were no exceedances of the 2016 U.S. Environmental Protection Agency health advisory of 70 nanograms per liter (ng/L) perfluorooctanoic acid plus perfluorooctane sulfonic acid. Twenty-two sites were resampled and showed similar signatures, excluding some springs. Total PFAS concentrations ranged from 0.91 to 80.3 ng/L. The most frequently detected PFAS at groundwater sites were perfluorobutanesulfonic acid (PFBS; 11 sites), perfluoropentanoic acid (10 sites), and perfluorohexanoic acid (9 sites). Correlations were found between certain PFAS compounds that suggest similar sources. PFAS were also correlated with tritium, DOC, and nitrate, which indicated that a presence of anthropogenic compounds could in turn indicate a likelihood of PFAS occurrence. In addition, a cluster analysis showed that varying geochemical processes and sources of anthropogenic compounds likely contribute to the PFAS signature of each groundwater sample.

Surface-water samples showed variable total PFAS concentrations ranging from 1.0 to 155.4 ng/L. Sites downstream from urban areas showed numerous PFAS detections. Some undeveloped areas where minimal PFAS detections would be expected had PFAS detections. Correlations between PFAS were found that suggested similar sources. Perfluoropentanoic acid and PFBS were the most frequently detected PFAS, and PFBS had the highest single concentration of 93 ng/L.

Results of the study provide an overview of PFAS occurrences in the water resources of New Mexico along with geochemical context and are used to identify areas for further scientific investigations that could further characterize PFAS occurrences in New Mexico.

Introduction

In New Mexico, water resources are scarce and can be particularly vulnerable to input from anthropogenic compounds (Langman and O’Nolan, 2005; Bexfield and others, 2011; Shephard and others, 2019; Flickinger and Shephard, 2022). Water quality is a function of local geology and climate as well as discharges from urban and agricultural regions. Drinking water in the State is obtained from both surface-water and groundwater sources.

Per- and polyfluoroalkyl substances (PFAS) are anthropogenic chemicals that have been widely used for the past 70 years (Lindstrom and others, 2011). PFAS are present in a number of consumer products and industrial applications, such as in firefighting foams, cookware, paper products, and coatings for textiles, and have been found in a variety of water resources throughout the United States (Boone and others, 2019). This class of compounds comprises thousands of chemicals, including perfluoro sulfonic acids, such as perfluorooctane sulfonic acid (PFOS), and perfluorocarboxylic acids, such as perfluorooctanoic acid (PFOA; Wang and others, 2017). As the use of these chemicals has grown, so has their ubiquity in the environment because of their highly persistent nature (Lindstrom and others, 2011). PFOA and PFOS have been investigated by the U.S. Environmental Protection Agency (EPA) and are considered harmful to human health and the environment (EPA, 2020). In 2016, the EPA established a health advisory limit of 70 nanograms per liter (ng/L) for PFOA and PFOS (EPA, 2022a). After this study was completed, in June 2022, the EPA issued a draft report with revised health advisory limits for PFOA and PFOS to 0.004 and 0.02 ng/L, respectively, and the EPA added health advisory limits for hexafluoropropylene oxide dimer acid and its ammonium salt (referred to as “GenX”) to 10 ng/L and perfluorobutanesulfonic acid (PFBS) to 2,000 ng/L (EPA, 2022a). Point sources, such as firefighting training areas, industrial facilities, and wastewater treatment plants, have been found to contribute PFAS into the water cycle, including as components of runoff and groundwater infiltration (Hu and others, 2016). At 25 drinking water plants across the United States, Boone and others (2019) analyzed paired samples from sources (untreated) and after treatment for 17 PFAS with reporting levels ranging from 0.032 to 0.56 ng/L, and detectable PFAS were found in all samples. Six PFAS were listed in drinking water in the EPA’s Third Unregulated Contaminant Monitoring Rule (EPA, 2022d). According to Crone and others (2019), 4 percent of water systems where samples were collected at entry points to the distribution system reported at least one detectable PFAS, where reporting levels ranged from 10 to 90 ng/L, and 1.3 percent of water systems reported results above the 2016 health advisory limits. There is evidence that exposure may lead to human reproductive and developmental problems as well as adverse liver, kidney, and immunological effects (EPA, 2020).

PFAS have been detected in public and private drinking water, springs, and surface waters in New Mexico (New Mexico Environment Department [NMED], 2020; Intellus New Mexico, 2020). More than 1,700 industry facility sites may be handling PFAS in New Mexico, according to the EPA Enforcement and Compliance History Online database (EPA, 2022b). There are known or suspected PFAS detections across the State, including those at Air Force bases, armories, a missile range, and an aviation support facility (EPA, 2022b). The NMED has investigated known PFAS concentrations at and around Cannon Air Force Base (Curry County) and Holloman Air Force Base (Otero County). The NMED, in conjunction with the New Mexico Department of Health and the U.S. Air Force, conducted sampling at the bases from 2016 through 2019. Twenty-one PFAS were analyzed using EPA Method 537 and 537 M. At Cannon Air Force Base, the highest total PFAS concentration was 56,504 ng/L in a Cannon Air Force Base monitoring well. At Holloman Air Force Base, the highest total PFAS concentration was 2,454,500 ng/L in a Holloman Air Force Base monitoring well (NMED, 2020). The NMED Department of Energy Oversight Bureau samples surface water and groundwater PFAS at Los Alamos National Laboratory and in 2019 the maximum concentration for an individual PFAS compound was 16.5 ng/L of PFOS (Intellus New Mexico, 2020). Although these areas in New Mexico are known to be affected by PFAS, the presence and distribution of PFAS in water resources across the State of New Mexico are not well characterized. The U.S. Geological Survey (USGS) assessed the presence of PFAS in surface-water and groundwater resources throughout New Mexico. The presence of PFAS was assessed in samples from representative locations, including urban, agricultural, and natural landscapes. Geochemical, isotopic, and wastewater tracer analytes were also assessed to better understand the groundwater evolution (chemical changes as water moves through the subsurface), which provides information regarding travel time of groundwater, mixing from different sources, recharge elevation, water rock interaction, and the potential surface-water sources. The results of this study will help to establish baseline PFAS occurrence in the water resources of New Mexico, provide geochemical context for groundwater and surface-water evolution related to understanding the presence or absence of PFAS compounds in those waters, and inform sampling efforts focused in areas where environmental PFAS detections are found.

Purpose and Scope

This report documents the assessment of per- and polyfluoroalkyl substances in water resources of New Mexico during 2020–21. Surface-water samples were collected from every major river in the State, and groundwater samples were collected from larger urban areas and less developed counties. The extent of PFAS concentrations is discussed, as well as the other associated geochemical data that were collected, for both groundwater and surface-water locations across the State of New Mexico.

Description of Study Area

The study area encompasses large areas of the State of New Mexico. Climate is described below, as well as surface-water hydrology, by watershed, and groundwater hydrology, by aquifer.

Climate

The topography of New Mexico ranges from high elevation forested mountains to lower elevation deserts. Except in the mountainous regions, the climate is primarily arid to semiarid. Average annual precipitation across New Mexico for 1980–2010 ranged from 6 inches in lower elevation areas of northwestern and southern New Mexico to 52 inches in higher elevation areas of northern New Mexico (New Mexico Office of the State Engineer/Interstate Stream Commission, 2018). Precipitation as snowfall in the winter months is a substantial source of surface-water and aquifer recharge and drives most of the streamflow in the Rio Grande in the northern portion of the State. Summer thunderstorms, known as monsoons, are also a highly variable source of precipitation and drive streamflow in the southern part of the State (Moeser and others, 2021).

Groundwater Hydrogeologic Setting

Groundwater sampling locations (117 groundwater well sites) were selected in populated areas across the State, which were also located in unconfined surficial aquifers (fig. 1, table 1). The majority of these wells supply public water systems. Because the majority of these wells were part of public water systems, it should be noted that the wells were sampled prior to any water treatment. Additionally, to provide a comprehensive assessment of PFAS in sources of water to those public water systems, springs and surface-water diversions within those systems were also sampled for the same constituents as the groundwater samples (table 1). Diversions, as defined by USGS, are locations where water is withdrawn or diverted from a surface-water body. For example, a diversion could be a point where water is diverted from a river into a water system or a point where water is withdrawn from a reservoir (USGS, 2022b). Diversions, while technically representing surface water, were analyzed for groundwater constituents because they were part of public supplies that consisted mostly of groundwater and (or) springs (table 1). However, the analytical results for surface-water diversion samples are not included with groundwater analytical results because they do not represent groundwater due to the diversions being derived from surface-water inputs. Springs are considered representative of groundwater chemistry because each is a location where groundwater emerges at land surface at the spring locations. Major aquifers or aquifer systems that were sampled included the Rio Grande aquifer system (39 groundwater wells and 3 surface-water diversions), the High Plains aquifer (52 groundwater wells), the Colorado Plateaus aquifers (5 groundwater wells), and the Roswell Basin aquifer system (4 groundwater wells; fig. 1). Forty-four sites are located in other surficial aquifers; of these, 24 are springs and 17 are wells.

The Rio Grande aquifer system (fig. 1) is a 70,000-square-mile (mi^2) area of interconnected basin-fill deposits in southern Colorado, New Mexico, and western Texas (Robson and Banta, 1995). The Rio Grande headwaters are located in southern Colorado, from which it flows southward through New Mexico from deep canyons north of Santa Fe, through broad basins and valleys, to the Texas State line. The Rio Grande rift is the primary geologic feature of the system, and the aquifer ranges in thickness from about 20,000 feet (ft) near Albuquerque, N. Mex., to 2,000 ft near El Paso, Texas. The Quaternary and Tertiary Santa Fe Group is the principal hydrologic member of the system and consists primarily of gravel, sand, and interbedded clays, and lesser amounts of lava flows, tuffs, and breccias. Recharge is primarily from precipitation in mountainous areas, seepage from the Rio Grande and its tributaries, as well as from irrigation conveyance structures and return flow (Houston and others, 2021). Jurgens and others (2022) characterized the age distribution for groundwater in 21 principal aquifers across the United States, including the Rio Grande aquifer system, and determined that if the principal aquifer contained modern water (1953 or newer), the aquifer could be susceptible to land-surface contamination. Jurgens and others (2022) found that the Rio Grande aquifer system had approximately 15 percent modern water and may be less susceptible to land-surface contamination.

The High Plains aquifer occupies a 174,000-mi^2 area that extends across parts of several States, including eastern New Mexico (fig. 1). The aquifer primarily consists of unconsolidated gravel, sand, and silt, and the Ogallala Formation is the principal hydrologic unit. The Miocene and early Pliocene Ogallala Formation was deposited by streams and therefore consists of deposits of variable thickness that range from 0 to 500 ft in buried paleochannels (Robson and Banta, 1995). Recharge to the High Plains aquifer is primarily from precipitation infiltration, irrigation water infiltration, or seepage from surface water. Jurgens and others (2022) determined that the High Plains aquifer contained approximately 30 percent modern water.

The Colorado Plateaus aquifers encompass 110,000 mi^2, including northwestern New Mexico (fig. 1). Four principal aquifers compose the system, with the two in New Mexico being the Mesaverde aquifer and the Dakota-Glen Canyon aquifer system (Robson and Banta, 1995). Study sites 1, 2, and 3 are in the Farmington area along the San Juan and Animas Rivers and vary in hydrogeologic setting. Site 1 (well depth, 145 ft) and site 2 (well depth, 40 ft) are not located in the Mesaverde aquifer according to Stewart (2018) and are in smaller, less productive aquifers. Site 1 is completed in the Pictured Cliffs Sandstone, and site 2 is completed in Naha and Tsegi eolian deposits (Stewart, 2018). The site 3 well is shallow and completed at 23 ft in alluvium rather than in one of the principal aquifers. Wells at sites 7 and 8 are around 2,000 ft deep, and they are likely completed in the Dakota-Glen Canyon aquifer system, which is composed of several sandstone and conglomerate water-yielding units (Robson and Banta, 1995). Recharge to these aquifers has been identified along outcrops forming structural boundaries, as water enters the groundwater system through these outcrops. Recharge also enters from stream-channel loss as streams cross the outcrops (Craigg, 2001). Newer studies have shown that there are some anthropogenic recharge sources in the basin, such as seepage from irrigation and leaking water and sewer lines (Robertson and others, 2016). Jurgens and others (2022) determined that the Colorado Plateaus aquifers contained approximately 20 percent modern water.

The Roswell Basin aquifer system occupies a 12,000-mi^2 area in southeastern New Mexico (fig. 1) and is composed of an alluvial aquifer and an underlying carbonate-rock aquifer. Groundwater is primarily present in the San Andres Limestone and the overlying Queen and Grayburg Formations (Robson and Banta, 1995). The alluvium overlying the carbonate rocks is generally west of the Pecos River and ranges in thickness from 150 to 300 ft. Recharge is mainly from precipitation in the outcrop areas of the San Andres Limestone and the alluvium. Additional recharge occurs from losing streams, as well as through sinkholes and solution fractures (Land and Newton, 2008).

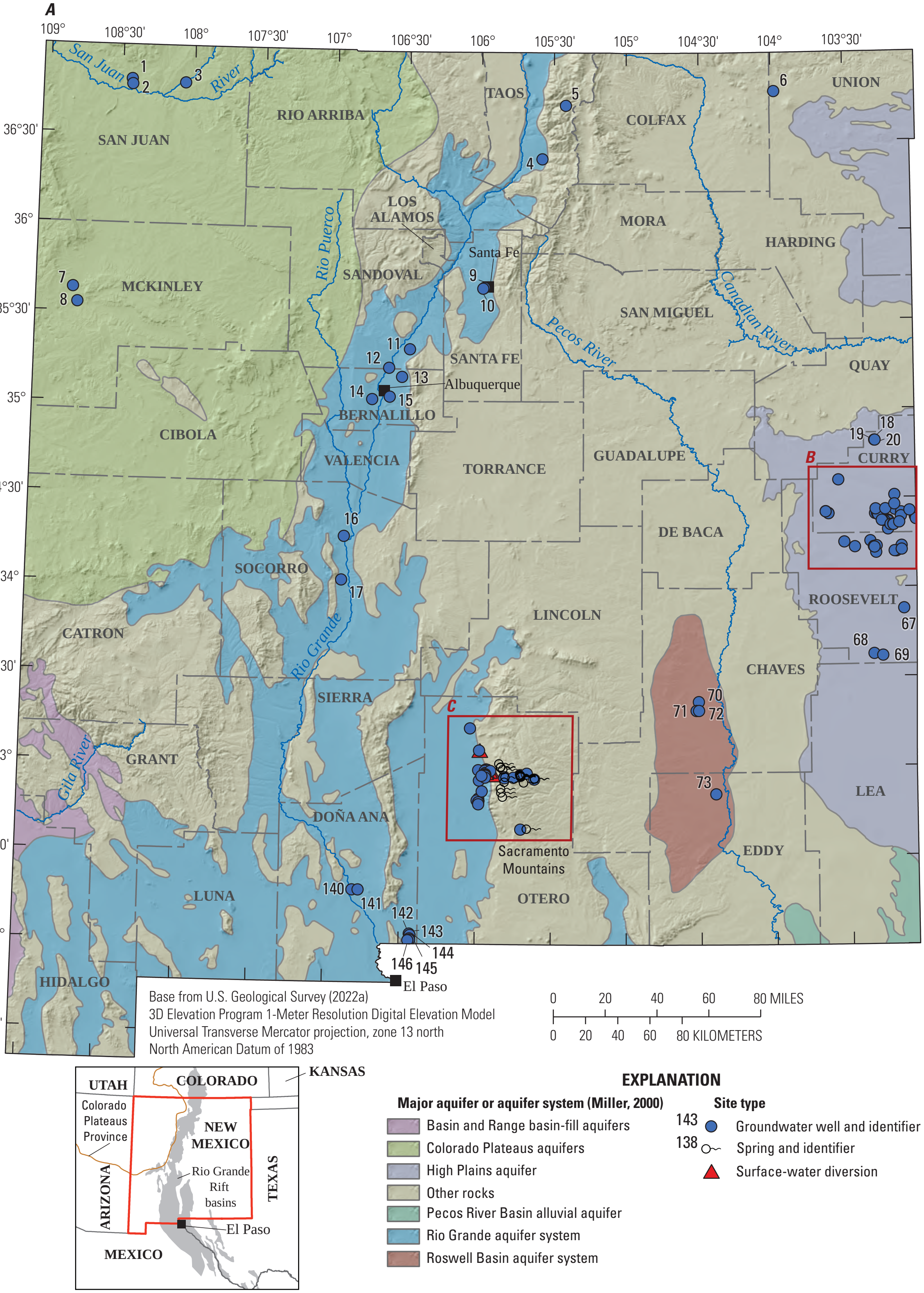
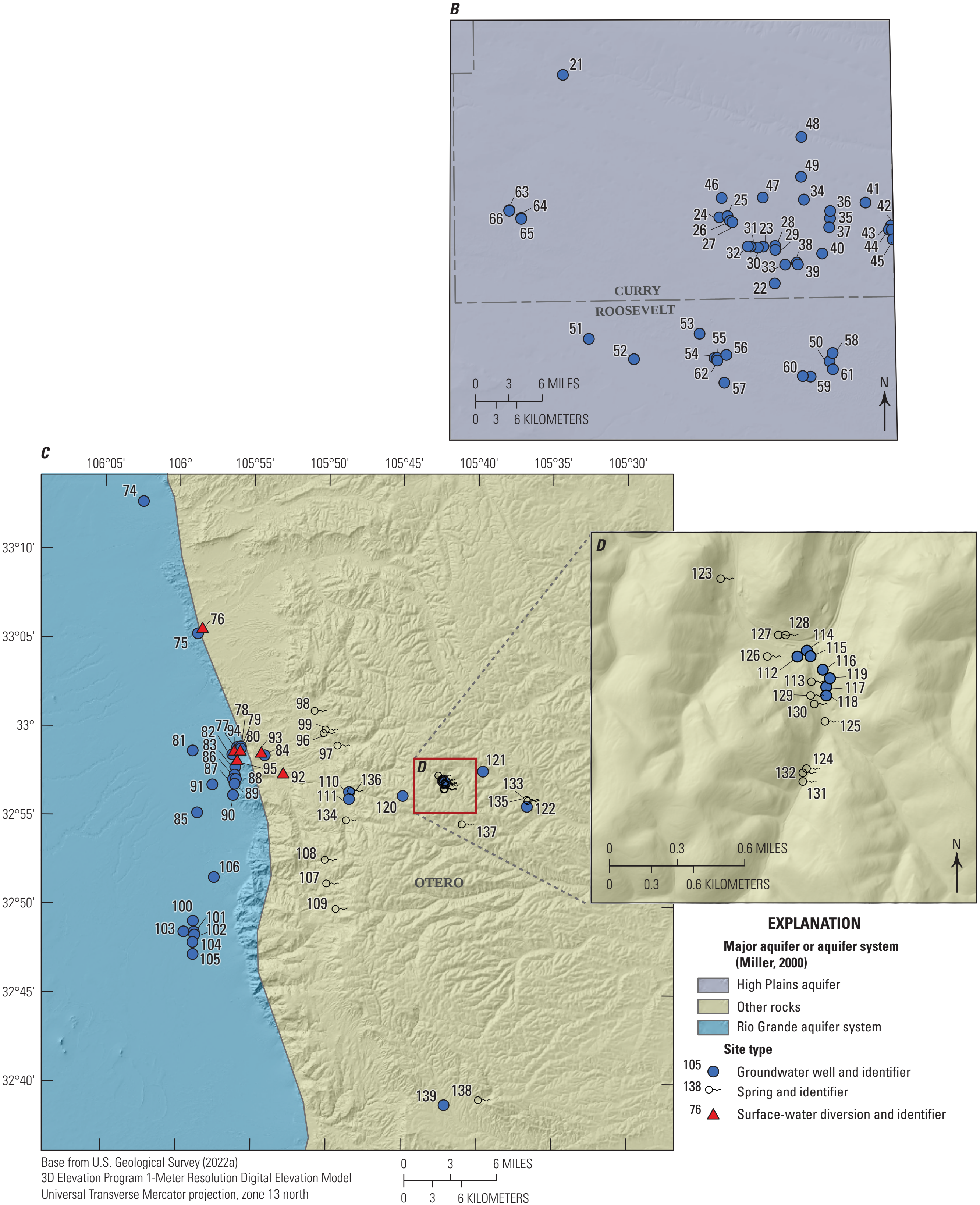


Figure 1. Per- and polyfluoroalkyl substances groundwater well, spring, and surface-water diversion sampling locations and major aquifers or aquifer systems *A*, across New Mexico, *B*, in parts of Curry and Roosevelt Counties, *C*, in part of Otero County, and *D*, in a high-mountain system in Otero County.



EXPLANATION

Major aquifer or aquifer system (Miller, 2000)

- ▨ High Plains aquifer
- ▨ Other rocks
- ▨ Rio Grande aquifer system

Site type

- 105 ● Groundwater well and identifier
- 138 ○~ Spring and identifier
- 76 ▲ Surface-water diversion and identifier

Base from U.S. Geological Survey (2022a)
3D Elevation Program 1-Meter Resolution Digital Elevation Model
Universal Transverse Mercator projection, zone 13 north
North American Datum of 1983

Figure 1..—Continued

Table 1. Groundwater wells, springs, and surface-water diversions sampled for per- and polyfluoroalkyl substances (PFAS), with applicable well and aquifer information.

[USGS, U.S. Geological Survey. Site type: GW, groundwater; FA-DV, diversion; SP, spring. Aquifer name: CPA, Colorado Plateaus aquifers; RGAS, Rio Grande aquifer system; NA, not applicable or available; RBAS, Roswell Basin aquifer system; HPA, High Plains aquifer. Rock type, unit, or formation: OR (PCS), other rocks (Pictured Cliffs Sandstone); OR (NTED), other rocks (Naha and Tsegi eolian deposits); OR (A), other rocks (alluvium); USG, unconsolidated sand and gravel aquifers; OR (TIRISC), other rocks (Tertiary intrusive rocks of intermediate to silicic composition); OR (BTLNV), other rocks (basaltic tephra and lavas near vents); SA, sandstone aquifers; CRA, carbonate-rock aquifers; OR (AF), other rocks (Abo Formation); OR (BF), other rocks (Bursum Formation of Madera Group); OR (YF), other rocks (Yeso Formation); OR (SAF), other rocks (San Andres Limestone)]

Report identification number	USGS site number	Site name	Site type	Sample frequency	Well depth (feet)	Aquifer name	Rock type, unit, or formation
1	364823108255901	30N.15W.20.22	GW	1	145	CPA	OR (PCS)
2	364642108254201	30N.15W.33.11	GW	1	40	CPA	OR (NTED)
3	364732108034101	30N.12W.23.443 4	GW	1	23	CPA	OR (A)
4	362357105344401	25N.13E.17.323	GW	1	300	RGAS	USG
5	364158105250802	29N.14E.35.343	GW	1	68	NA	OR (TIRISC)
6	364643103583701	29N.28E.05.234	GW	1	680.5	NA	OR (BTLNV)
7	353814108473001	16N.18W.07.1111	GW	1	2,147	CPA	SA
8	353314108453101	15N.18W.04.332	GW	1	1,860	CPA	SA
9	354041105581301	17N.09E.27.232	GW	1	740	RGAS	USG
10	354022105584701	17N.09E.27.31413	GW	1	809	RGAS	USG
11	351944106283601	13N.04E.25.132	GW	1	755	RGAS	USG
12	351325106370101	12N.03E.33	GW	1	280	RGAS	USG
13	351025106323801	11N.04E.21.121	GW	1	1,723	RGAS	USG
14	350249106434201	10N.02E.27.444	GW	1	1,133	RGAS	USG
15	350343106363301	10N.03E.27.414	GW	1	1,276	RGAS	USG
16	341643106541601	01N.01W.36	GW	1	520	RGAS	USG
17	340204106550301	03S.01W.23.213	GW	1	505	RGAS	USG
18	344916103190001	07N.34E.23.112 1	GW	3	230	HPA	USG
19	344916103185801	07N.34E.23.112 2	GW	2	230	HPA	USG
20	344915103185101	07N.34E.23.121 3	GW	1	220	HPA	USG
21	343605103334901	04N.32E.02.121	GW	1	NA	HPA	USG
22	341921103135901	01N.35E.11.424	GW	1	NA	HPA	USG
23	342217103150001	02N.353E.27.242	GW	2	NA	HPA	USG
24	342439103190901	02N.35E.07.311	GW	2	430	HPA	USG
25	342444103182201	02N.35E.07.421 1	GW	2	400	HPA	USG
26	342418103180601	02N.35E.07.44442 2146	GW	2	350	HPA	USG
27	342415103175501	02N.35E.17.1212	GW	1	NA	HPA	USG
28	342219103135301	02N.35E.25.131	GW	1	NA	HPA	USG

Table 1. Groundwater wells, springs, and surface-water diversions sampled for per- and polyfluoroalkyl substances (PFAS), with applicable well and aquifer information.—Continued

[USGS, U.S. Geological Survey. Site type: GW, groundwater; FA-DV, diversion; SP, spring. Aquifer name: CPA, Colorado Plateaus aquifers; RGAS, Rio Grande aquifer system; NA, not applicable or available; RBAS, Roswell Basin aquifer system; HPA, High Plains aquifer. Rock type, unit, or formation: OR (PCS), other rocks (Pictured Cliffs Sandstone); OR (NTED), other rocks (Naha and Tsegi eolian deposits); OR (A), other rocks (alluvium); USG, unconsolidated sand and gravel aquifers; OR (TIRISC), other rocks (Tertiary intrusive rocks of intermediate to silicic composition); OR (BTLNV), other rocks (basaltic tephra and lavas near vents); SA, sandstone aquifers; CRA, carbonate-rock aquifers; OR (AF), other rocks (Abo Formation); OR (BF), other rocks (Bursum Formation of Madera Group); OR (YF), other rocks (Yeso Formation); OR (SAF), other rocks (San Andres Limestone)]

Report identification number	USGS site number	Site name	Site type	Sample frequency	Well depth (feet)	Aquifer name	Rock type, unit, or formation
29	342200103135301	02N.35E.25.313	GW	1	NA	HPA	USG
30	342213103153201	02N.35E.27.442	GW	1	NA	HPA	USG
31	342218103161301	02N.35E.28.223	GW	1	NA	HPA	USG
32	342218103162801	02N.35E.28.231	GW	1	NA	HPA	USG
33	342050103125801	02N.35E.36.444	GW	1	NA	HPA	USG
34	342556103110401	02N.36E.05.212	GW	1	NA	HPA	USG
35	342425103083701	02N.36E.10.444	GW	1	NA	HPA	USG
36	342500103083501	02N.36E.11.113	GW	1	NA	HPA	USG
37	342342103084201	02N.36E.15.441	GW	1	375	HPA	USG
38	342058103115101	02N.36E.31.442	GW	1	NA	HPA	USG
39	342049103114501	02N.36E.32.111	GW	1	NA	HPA	USG
40	342139103092501	02N.36E.34.221	GW	1	NA	HPA	USG
41	342537103051201	02N.37E.05.134	GW	1	389	HPA	USG
42	342346103024901	02N.37E.15.412	GW	1	389	HPA	USG
43	342322103025301	02N.37E.15.43341	GW	2	385	HPA	USG
44	342326103024501	02N.37E.15.443	GW	3	392	HPA	USG
45	342220103023302	02N.37E.22.432342A	GW	2	400	HPA	USG
46	342610103185401	03N.35E.31.341 2	GW	2	400	HPA	USG
47	342609103145901	03N.35E.34.441	GW	1	NA	HPA	USG
48	343053103111201	03N.36E.05.233	GW	2	397	HPA	USG
49	342744103111801	03N.36E.29.122	GW	1	NA	HPA	USG
50	341309103085401	01.36E.15.423	GW	1	201	HPA	USG
51	341513103314501	01S.32E.01.242	GW	1	NA	HPA	USG
52	341334103272901	01S.33E.15.224	GW	1	NA	HPA	USG
53	341530103211301	01S.34E.02.111	GW	1	90	HPA	USG
54	341333103195001	01S.34E.13.114 3	GW	1	120	HPA	USG
55	341333103193501	01S.34E.13.231 5	GW	1	120	HPA	USG

Table 1. Groundwater wells, springs, and surface-water diversions sampled for per- and polyfluoroalkyl substances (PFAS), with applicable well and aquifer information.—Continued

[USGS, U.S. Geological Survey. Site type: GW, groundwater; FA-DV, diversion; SP, spring. Aquifer name: CPA, Colorado Plateaus aquifers; RGAS, Rio Grande aquifer system; NA, not applicable or available; RBAS, Roswell Basin aquifer system; HPA, High Plains aquifer. Rock type, unit, or formation: OR (PCS), other rocks (Pictured Cliffs Sandstone); OR (NTED), other rocks (Naha and Tsegi eolian deposits); OR (A), other rocks (alluvium); USG, unconsolidated sand and gravel aquifers; OR (TIRISC), other rocks (Tertiary intrusive rocks of intermediate to silicic composition); OR (BTLNV), other rocks (basaltic tephra and lavas near vents); SA, sandstone aquifers; CRA, carbonate-rock aquifers; OR (AF), other rocks (Abo Formation); OR (BF), other rocks (Bursum Formation of Madera Group); OR (YF), other rocks (Yeso Formation); OR (SAF), other rocks (San Andres Limestone)]

Report identification number	USGS site number	Site name	Site type	Sample frequency	Well depth (feet)	Aquifer name	Rock type, unit, or formation
56	341347103184201	01S.35E.18.121 7	GW	1	115	HPA	USG
57	341135103185601	01S.35E.30.312	GW	1	NA	HPA	USG
58	341349103083401	01S.36E.11.33332	GW	1	200	HPA	USG
59	341154103103801	01S.36E.28.111311	GW	1	172	HPA	USG
60	341200103112801	01S.36E.29.121	GW	1	NA	HPA	USG
61	341230103083601	01S.36E.23.331	GW	1	208	HPA	USG
62	341321103193401	01S.34E.13.234	GW	1	120	HPA	USG
63	342528103390901	02N.31E.01.31	GW	2	110	HPA	USG
64	342450103380101	02N.32E.07.133 3	GW	2	110	HPA	USG
65	342446103380101	02N.32E.07.311 4	GW	1	120	HPA	USG
66	342525103390901	2N.31E.02.442 1	GW	2	110	HPA	USG
67	335247103080201	05S.36E.11.433 1	GW	1	189	HPA	USG
68	333737103201701	08S.35E.14.112	GW	1	NA	HPA	USG
69	333700103164701	08S.36E.17.422	GW	1	NA	HPA	USG
70	332137104303901	11S.24E.16.142 12	GW	1	344	RBAS	CRA
71	331843104315001	11S.24E.32.411 4	GW	1	346	RBAS	CRA
72	331843104305001	11S.24E.33.322 1	GW	1	590	RBAS	CRA
73	325041104240701	17S.26E.08.432	GW	1	1,158	RBAS	CRA
74	331238106022501	13S.09E.01.314	GW	1	NA	RGAS	USG
75	330515105584401	14S.10E.21.223	FA-DV	1	NA	RGAS	USG
76	330539105582601	14S.10E.15.312	FA-DV	1	NA	NA	OR (AF)
77	325846105561501	15S.10E.25.314	GW	1	640	RGAS	USG
78	325852105560301	15S.10E.25.321 2	GW	1	640	RGAS	USG
79	325854105554801	15S.10E.25.411	GW	1	710	RGAS	USG
80	325847105554801	15S.10E.25.413 3	GW	1	900	RGAS	USG
81	325839105590101	15S.10E.28.431 1	GW	1	275	RGAS	USG
82	325827105562201	15S.10E.36.111B	GW	2	936	RGAS	USG

Table 1. Groundwater wells, springs, and surface-water diversions sampled for per- and polyfluoroalkyl substances (PFAS), with applicable well and aquifer information.—Continued

[USGS, U.S. Geological Survey. Site type: GW, groundwater; FA-DV, diversion; SP, spring. Aquifer name: CPA, Colorado Plateaus aquifers; RGAS, Rio Grande aquifer system; NA, not applicable or available; RBAS, Roswell Basin aquifer system; HPA, High Plains aquifer. Rock type, unit, or formation: OR (PCS), other rocks (Pictured Cliffs Sandstone); OR (NTED), other rocks (Naha and Tsegi eolian deposits); OR (A), other rocks (alluvium); USG, unconsolidated sand and gravel aquifers; OR (TIRISC), other rocks (Tertiary intrusive rocks of intermediate to silicic composition); OR (BTLNV), other rocks (basaltic tephra and lavas near vents); SA, sandstone aquifers; CRA, carbonate-rock aquifers; OR (AF), other rocks (Abo Formation); OR (BF), other rocks (Bursum Formation of Madera Group); OR (YF), other rocks (Yeso Formation); OR (SAF), other rocks (San Andres Limestone)]

Report identification number	USGS site number	Site name	Site type	Sample frequency	Well depth (feet)	Aquifer name	Rock type, unit, or formation
83	325745105561001	15S.10E.36.332	GW	1	995	RGAS	USG
84	325825105541201	15S.11E.31.222 IG2	GW	1	NA	NA	OR (BF)
85	325510105584101	16S.09E.13.332 1	GW	1	226	RGAS	USG
86	325717105560601	16S.10E.05.224 4	GW	1	780	RGAS	USG
87	325704105561801	16S.10E.05.241 3	GW	1	880	RGAS	USG
88	325704105560701	16S.10E.05.242 2	GW	1	990	RGAS	USG
89	325648105561201	16S.10E.05.422 6	GW	1	844	RGAS	USG
90	325610105561801	16S.10E.05.443 7	GW	1	750	RGAS	USG
91	325645105574101	16S.10E.06.314 1	GW	1	270	RGAS	USG
92	325727105525201	16S.10E.01.123	FA-DV	1	NA	NA	OR (BF)
93	325840105542601	15S.11E.31.221 2	FA-DV	1	NA	NA	OR (BF)
94	325848105554701	15S.10E.25.243 INT	FA-DV	1	NA	RGAS	USG
95	325813105560301	15S.10E.36.141	FA-DV	1	NA	RGAS	USG
96	325942105501901	15S.11E.23.421	SP	1	NA	NA	OR (AF)
97	325901105492301	15S.11E.25.231	SP	1	NA	NA	OR (AF)
98	330057105505601	15S.11E.14.114	SP	1	NA	NA	OR (YF)
99	325954105501201	15S.11E.23.241	SP	3	NA	NA	OR (AF)
100	324904105585401	17S.09E.23.442 4	GW	1	200	RGAS	USG
101	324827105585001	17S.09E.25.133 1	GW	1	250	RGAS	USG
102	324817105584801	17S.09E.25.313 2	GW	1	300	RGAS	USG
103	324827105593201	17S.09E.26.143 5	GW	1	250	RGAS	USG
104	324752105585301	17S.09E.35.224	GW	2	300	RGAS	USG
105	324711105585201	17S.09E.35.444	GW	2	297	RGAS	USG
106	325132105573201	17S.10E.06.111	GW	1	780	RGAS	USG
107	325114105500401	17S.11E.04.131	SP	1	NA	NA	OR (AF)
108	325234105501101	16S.11E.32.221	SP	1	NA	NA	OR (AF)
109	324948105492601	17S.11E.16.232	SP	1	NA	NA	OR (YF)

Table 1. Groundwater wells, springs, and surface-water diversions sampled for per- and polyfluoroalkyl substances (PFAS), with applicable well and aquifer information.—Continued

[USGS, U.S. Geological Survey. Site type: GW, groundwater; FA-DV, diversion; SP, spring. Aquifer name: CPA, Colorado Plateaus aquifers; RGAS, Rio Grande aquifer system; NA, not applicable or available; RBAS, Roswell Basin aquifer system; HPA, High Plains aquifer. Rock type, unit, or formation: OR (PCS), other rocks (Pictured Cliffs Sandstone); OR (NTED), other rocks (Naha and Tsegi eolian deposits); OR (A), other rocks (alluvium); USG, unconsolidated sand and gravel aquifers; OR (TIRISC), other rocks (Tertiary intrusive rocks of intermediate to silicic composition); OR (BTLNV), other rocks (basaltic tephra and lavas near vents); SA, sandstone aquifers; CRA, carbonate-rock aquifers; OR (AF), other rocks (Abo Formation); OR (BF), other rocks (Bursum Formation of Madera Group); OR (YF), other rocks (Yeso Formation); OR (SAF), other rocks (San Andres Limestone)]

Report identification number	USGS site number	Site name	Site type	Sample frequency	Well depth (feet)	Aquifer name	Rock type, unit, or formation
110	325623105483301	16S.11E.03.332 2	GW	1	72	NA	OR (YF)
111	325559105483301	16S.11E.10.112 1	GW	1	150	NA	OR (YF)
112	325703105421801	16S.12E.03.142 6	GW	1	380	NA	OR (YF)
113	325657105421301	16S.12E.03.1424	SP	1	NA	NA	OR (YF)
114	325704105421501	16S.12E.03.142B	GW	1	158	NA	OR (YF)
115	325703105421401	16S.12E.03.142D	GW	1	282	NA	OR (YF)
116	325700105421101	16S.12E.03.231 4	GW	1	500	NA	OR (YF)
117	325656105421001	16S.12E.03.233 5	GW	1	360	NA	OR (YF)
118	325654105421001	16S.12E.03.233 8	GW	1	400	NA	OR (YF)
119	325658105420901	16S.12E.03.233 9	GW	1	400	NA	OR (YF)
120	325611105445801	16S.12E.06.44 1	GW	1	335	NA	OR (SAF)
121	325735105393701	16S.13E.06.111 1	GW	1	567	NA	OR (YF)
122	325537105364001	16S.13E.09.442	GW	1	652	NA	OR (YF)
123	325721105423801	16S.12E.03.113 1	SP	1	NA	NA	OR (YF)
124	325637105421401	16S.12E.03.321 10	SP	2	NA	NA	OR (YF)
125	325648105420901	16S.12E.03.233 11	SP	2	NA	NA	OR (YF)
126	325703105422501	16S.12E.03.141 12	SP	1	NA	NA	OR (YF)
127	325708105422201	16S.12E.03.141 2	SP	1	NA	NA	OR (YF)
128	325708105422001	16S.12E.03.141 3	SP	2	NA	NA	OR (YF)
129	325654105421301	16S.12E.03.144 4	SP	1	NA	NA	OR (YF)
130	325652105421201	16S.12E.03.144 5	SP	1	NA	NA	OR (YF)
131	325634105421501	16S.12E.03.321 8	SP	1	NA	NA	OR (YF)
132	325636105421501	16S.12E.03.321 9	SP	1	NA	NA	OR (YF)
133	325601105364401	16S.13E.09.224 1	SP	1	NA	NA	OR (YF)
134	325448105484701	16S.11E.16.244	SP	1	NA	NA	OR (YF)
135	325557105364001	16S.13E.09.224 2	SP	1	NA	NA	OR (YF)
136	325627105482701	16S.11E.03.323	SP	1	NA	NA	OR (YF)

Table 1. Groundwater wells, springs, and surface-water diversions sampled for per- and polyfluoroalkyl substances (PFAS), with applicable well and aquifer information.—Continued

[USGS, U.S. Geological Survey. Site type: GW, groundwater; FA-DV, diversion; SP, spring. Aquifer name: CPA, Colorado Plateaus aquifers; RGAS, Rio Grande aquifer system; NA, not applicable or available; RBAS, Roswell Basin aquifer system; HPA, High Plains aquifer. Rock type, unit, or formation: OR (PCS), other rocks (Pictured Cliffs Sandstone); OR (NTED), other rocks (Naha and Tsegi eolian deposits); OR (A), other rocks (alluvium); USG, unconsolidated sand and gravel aquifers; OR (TIRISC), other rocks (Tertiary intrusive rocks of intermediate to silicic composition); OR (BTLNV), other rocks (basaltic tephra and lavas near vents); SA, sandstone aquifers; CRA, carbonate-rock aquifers; OR (AF), other rocks (Abo Formation); OR (BF), other rocks (Bursum Formation of Madera Group); OR (YF), other rocks (Yeso Formation); OR (SAF), other rocks (San Andres Limestone)]

Report identification number	USGS site number	Site name	Site type	Sample frequency	Well depth (feet)	Aquifer name	Rock type, unit, or formation
137	325437105410301	16S.12E.14.411	SP	1	NA	NA	OR (YF)
138	323905105395101	19S.12E.13.424B	SP	1	NA	NA	OR (YF)
139	323847105420601	19S.12E.22.211	GW	1	1,200	NA	OR (YF)
140	321804106484001	23S.01E.14.344	GW	1	772	RGAS	USG
141	321806106461501	23S.02E.18.441	GW	1	700	RGAS	USG
142	320330106254801	26S.05E.09.421	GW	1	700	RGAS	USG
143	320302106253101	26S.05E.15.112	GW	1	710	RGAS	USG
144	320153106254101	26S.05E.22.133	GW	1	685	RGAS	USG
145	320126106254001	26S.05E.22.333	GW	1	737	RGAS	USG
146	320116106262101	26S.05E.28.121	GW	1	800	RGAS	USG
147	323805105414001	19S.12E.23.431	GW	1	NA	NA	OR (YF)

Approximately one-third of the study sites in table 1 did not fall within the aforementioned primary aquifer systems. Although most of these sites are located in southern New Mexico, two sites are located in north central and northeastern New Mexico (fig. 1). Site 5 is a relatively shallow well with a depth of 68 ft and, based on the surficial geology map of New Mexico (Horton, 2017), is located in Tertiary intrusive rock. Site 6, a groundwater well, is 680 ft deep and is located in Quaternary volcanic rocks. In southern New Mexico, most of the sites (including spring sites 98, 109, 113, and 123–138, and groundwater well sites 110–112, 114–119, 121–122, and 139; table 1) are located in the Yeso Formation (a sandstone; Horton, 2017). Sites 96, 97, and 99 (springs) are located in the Abo Formation (a sandstone; Horton, 2017). Site 84 (groundwater well) is located in the Bursum Formation of the Madera Group (shale), and site 120 (groundwater well) is located in the San Andres Limestone (Horton, 2017).

Surface-Water Hydrologic Setting

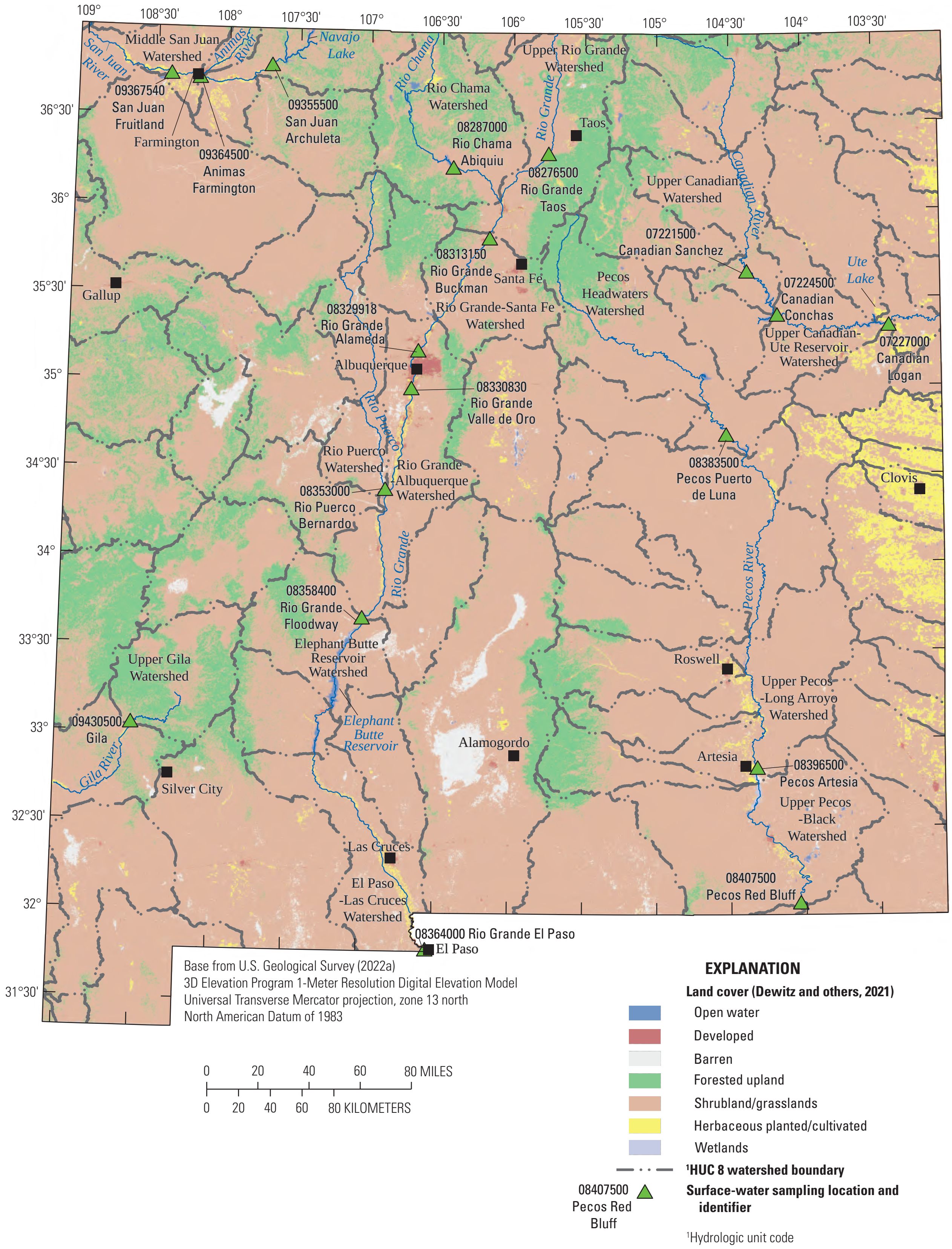
Surface-water samples were collected from 18 established USGS streamgaging sites across New Mexico (fig. 2, table 2). The rivers sampled were the Animas River, San Juan River, Canadian River, Gila River, Rio Grande, Rio Chama, Rio Puerco, and Pecos River. Land cover was evaluated near each surface-water site (fig. 2, table 3) using the near-site watershed method as described in Medalie and others (2020) and in the “Methods” section herein.

The Animas and San Juan Rivers flow through the northwestern portion of the State (fig. 2). Both rivers supply water valuable for municipal, agricultural, cultural, and recreational uses. From its headwaters in southwestern Colorado, the Animas River flows southwest until it eventually joins the San Juan River in Farmington, N. Mex. (EPA, 2022c). The Animas River at Farmington, N. Mex. sampling site (herein referred to as “Animas Farmington”; site number 09364500) is approximately 1.25 miles (mi) upstream from the confluence with the San Juan River. The land cover near this sampling site is 72 percent shrubland and 14 percent developed (fig. 2, table 3). The San Juan River enters New Mexico through Navajo Lake, a reservoir used for flood control; water supply for irrigation, domestic, and industrial use; water storage; hydropower; and recreational purposes (EPA, 2022c). San Juan River near Archuleta, N. Mex. (herein referred to as “San Juan Archuleta”; site number 09355500), one of the two sampling sites on the San Juan River, is approximately 6 mi downstream from Navajo Lake (fig. 2). This site is surrounded by 62 percent shrubland and approximately 27 percent forested land. From Navajo Lake, the San Juan River flows through agricultural land in the Colorado Plateau until it reaches Farmington, N. Mex., and is joined by the Animas River at the Animas Farmington site. Below the confluence with the Animas River, the San Juan River flows westward, where it provides irrigation water for agricultural communities, past Fruitland, N. Mex., at San Juan near Fruitland, N. Mex., sampling site (herein referred to as “San Juan Fruitland”; site number 09367540). The land cover near this site is 86 percent shrubland. The San Juan River then continues through northwestern New Mexico, flowing past two coal-fired power plants and through a sandstone canyon where it leaves New Mexico (EPA, 2022c). The sampling locations in the San Juan and Animas rivers were sampled seven to nine times throughout the project (table 2).

The headwaters of the Canadian River flow southeast through northeastern New Mexico and the river continues to flow eastward until it leaves the State (Oklahoma History Center, 2022). In downstream order, the three locations sampled along the Canadian River are: Canadian River near Sanchez, N. Mex. (herein referred to as “Canadian Sanchez”; site number 07221500); Canadian River below Conchas Dam (herein referred to as “Canadian Conchas”; site number 07224500); and Canadian River at Logan, N. Mex. (herein referred to as “Canadian Logan”; site number 07227000) (fig. 2). The Canadian River sites were only sampled one or two times throughout the project (table 2), and all three sites are dominated by shrubland land cover with little to no developed land (table 3).

The Gila River near Gila, N. Mex., sampling site (herein referred to as “Gila”; site number 09430500) is in the Upper Gila watershed in southwestern New Mexico (fig. 2). Much of the 5,532 mi of water courses in the Upper Gila watershed are intermittent streams that occasionally flow in the summer after thunderstorms (Natural Resources Conservation Service, 2022). Gila had a mean annual streamflow of about 156 cubic feet per second for 1927–2011 (Natural Resources Conservation Service, 2022). The Gila River was only sampled twice during the study (table 2), and the land cover near this site consists of approximately 73 percent forested land and 27 percent shrubland/grassland (table 3).

The headwaters of the Rio Grande are in southwestern Colorado, and six sites were sampled along the Rio Grande as it flows south through New Mexico (fig. 2). In downstream order, the sampled sites are Rio Grande below Taos Junction Bridge near Taos, N. Mex. (herein referred to as “Rio Grande Taos”; site number 08276500); Rio Grande above Buckman Diversion near White Rock, N. Mex. (herein referred to as “Rio Grande Buckman”; site number 08313150); Rio Grande at Alameda Bridge at Alameda, N. Mex. (herein referred to as “Rio Grande Alameda”; site number 08329918); Rio Grande at Valle de Oro, N. Mex. (herein referred to as “Rio Grande Valle de Oro”; site number 08330830); Rio Grande Floodway at San Marcial, N. Mex. (herein referred to as “Rio Grande Floodway”; site number 08358400), and Rio Grande at El Paso, Tex. (herein referred to as “Rio Grande El Paso”; site number 08364000). Depending on the location, these sites were sampled between 2 (Rio Grande Taos) and 13 (Rio Grande Valle de Oro) times (table 2), and the sampling frequency was variable and coordinated with other USGS activity in the study area. From northern New Mexico, the Rio Grande flows southward to the most upstream sampling site, Rio Grande Taos. This site is surrounded by about 75 percent shrubland/grassland land cover and 22 percent forested land



Base from U.S. Geological Survey (2022a)
3D Elevation Program 1-Meter Resolution Digital Elevation Model
Universal Transverse Mercator projection, zone 13 north
North American Datum of 1983

Figure 2. Per- and polyfluoroalkyl substances surface-water sampling locations across New Mexico with land cover, rivers, water bodies, and watersheds shown.

Table 2. Surface-water sites across New Mexico with location information, drainage area, and watershed information.

[Horizonal coordinate information is referenced to the North American Datum of 1983. USGS, U.S. Geological Survey; HUC, hydrologic unit code; N. Mex, New Mexico; Tex., Texas]

USGS site number	Site name	Report name	Sample frequency	Latitude (decimal degrees)	Longitude (decimal degrees)	Drainage area (square miles)	HUC 8 watershed	HUC 8 watershed name	HUC 8 watershed area (square miles)
07221500	Canadian River near Sanchez, N. Mex.	Canadian Sanchez	2	35.654833	−104.378611	6,015	11080003	Upper Canadian	2,054
07224500	Canadian River below Conchas Dam, N. Mex.	Canadian Conchas	1	35.408937	−104.169976	7,417	11080006	Upper Canadian-Ute Reservoir	2,239
07227000	Canadian River at Logan, N. Mex.	Canadian Logan	3	35.350000	−103.399722	11,141	11080006	Upper Canadian-Ute Reservoir	2,239
08287000	Rio Chama below Abiquiu Dam, N. Mex.	Rio Chama Abiquiu	4	36.237222	−106.417417	2,147	13020102	Rio Chama	3,158
08276500	Rio Grande below Taos Junction Bridge near Taos, N. Mex.	Rio Grande Taos	2	36.320033	−105.754444	9,730	13020101	Upper Rio Grande	3,254
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	Rio Grande Buckman	10	35.838417	−106.159083	14,360	13020201	Rio Grande-Santa Fe	1,872
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	Rio Grande Alameda	10	35.197722	−106.642778	17,129	13020203	Rio Grande-Albuquerque	3,216
08330830	Rio Grande at Valle de Oro, N. Mex.	Rio Grande Valle de Oro	13	34.983333	−106.686556	17,529	13020203	Rio Grande-Albuquerque	3,216
08353000	Rio Puerco near Bernardo, N. Mex.	Rio Puerco Bernardo	2	34.410278	−106.854444	6,437	13020204	Rio Puerco	2,112
08358400	Rio Grande Floodway at San Marcial, N. Mex.	Rio Grande Floodway	2	33.679083	−106.997000	27,700	13020211	Elephant Butte Reservoir	2,188
08364000	Rio Grande at El Paso, Tex.	Rio Grande El Paso	12	31.802885	−106.540822	32,210	13030102	El Paso-Las Cruces	5,519
08383500	Pecos River near Puerto de Luna, N. Mex.	Pecos Puerto de Luna	7	34.730083	−104.524911	3,970	13060001	Pecos Headwaters	3,481
08396500	Pecos River near Artesia, N. Mex.	Pecos Artesia	7	32.840861	−104.323833	15,300	13060007	Upper Pecos-Long Arroyo	3,201
08407500	Pecos River at Red Bluff, N. Mex.	Pecos Red Bluff	1	32.075192	−104.039436	19,540	13060011	Upper Pecos-Black	4,382
09355500	San Juan River near Archuleta, N. Mex.	San Juan Archuleta	8	36.801889	−107.698639	3,260	14080101	Upper San Juan	3,431

Table 2. Surface-water sites across New Mexico with location information, drainage area, and watershed information.—Continued

[Horizonal coordinate information is referenced to the North American Datum of 1983. USGS, U.S. Geological Survey; HUC, hydrologic unit code; N. Mex, New Mexico; Tex., Texas]

USGS site number	Site name	Report name	Sample frequency	Latitude (decimal degrees)	Longitude (decimal degrees)	Drainage area (square miles)	HUC 8 watershed	HUC 8 watershed name	HUC 8 watershed area (square miles)
09364500	Animas River at Farmington, N. Mex.	Animas Farmington	7	36.722500	−108.201750	1,360	14080104	Animas	1,370
09367540	San Juan River near Fruitland, N. Mex.	San Juan Fruitland	9	36.740279	−108.403135	7,950	14080105	Middle San Juan	1,945
09430500	Gila River near Gila, N. Mex.	Gila	2	33.061503	−108.537386	1,864	15040001	Upper Gila	1,982

Table 3. Land cover percentages within the near-site watershed of a surface-water sampling location, as determined by the methods in Medalie and others (2020).

[ID, identifier; USGS, U.S. Geological Survey; N. Mex., New Mexico; Tex., Texas]

USGS site number	Site name	Open water	Developed	Barren	Forested	Shrubland/ grassland	Herbaceous planted/ cultivated	Urban/ recreational grasses	Wetlands	Near-site land cover category
07221500	Canadian River near Sanchez, N. Mex.	0.0	0.0	0.0	13.4	86.3	0.3	0.0	0.0	Undeveloped
07224500	Canadian River below Conchas Dam, N. Mex.	12.5	0.3	0.0	0.3	86.9	0.0	0.0	0.0	Undeveloped
07227000	Canadian River at Logan, N. Mex.	7.6	0.6	0.0	0.1	72.0	19.7	0.0	0.0	Mixed
08287000	Rio Chama below Abiquiu Dam, N. Mex.	4.0	0.2	0.3	25.5	69.9	0.1	0.0	0.0	Undeveloped
08276500	Rio Grande below Taos Junction Bridge near Taos, N. Mex.	0.4	0.5	0.0	22.2	74.9	1.7	0.2	0.0	Undeveloped
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	0.4	2.2	1.0	10.4	84.3	1.6	0.1	0.0	Undeveloped
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	1.1	8.6	1.0	4.4	80.1	3.2	0.7	0.8	Mixed
08330830	Rio Grande at Valle de Oro, N. Mex.	1.1	40.3	1.2	0.6	49.4	3.8	2.6	1.1	Developed
08353000	Rio Puerco near Bernardo, N. Mex.	0.0	0.0	13.0	0.0	86.9	0.0	0.0	0.0	Undeveloped
08358400	Rio Grande Floodway at San Marcial, N. Mex.	1.2	0.2	0.6	1.7	95.4	0.1	0.0	0.9	Undeveloped
08364000	Rio Grande at El Paso, Tex.	0.5	39.6	0.7	0.4	49.0	9.9	0.0	0.0	Developed
08383500	Pecos River near Puerto de Luna, N. Mex.	0.0	0.0	0.1	0.0	98.4	1.5	0.0	0.0	Undeveloped
08396500	Pecos River near Artesia, N. Mex.	0.2	3.1	1.7	0.0	87.0	6.5	0.1	1.5	Undeveloped
08407500	Pecos River at Red Bluff, N. Mex.	0.4	0.1	2.4	0.0	96.7	0.4	0.0	0.0	Undeveloped
09355500	San Juan River near Archuleta, N. Mex.	9.7	0.1	0.5	27.3	62.4	0.0	0.0	0.0	Undeveloped
09364500	Animas River at Farmington, N. Mex.	2.0	13.7	0.5	0.5	72.0	10.0	1.3	0.0	Mixed
09367540	San Juan River near Fruitland, N. Mex.	1.2	1.9	0.2	0.1	85.8	10.5	0.3	0.0	Mixed
09430500	Gila River near Gila, N. Mex.	0.2	0.0	0.0	72.9	26.8	0.0	0.0	0.0	Undeveloped

cover (table 3). The Rio Grande continues from the Upper Rio Grande watershed to the confluence with the Rio Chama, which is the largest tributary to the Rio Grande (Natural Resources Conservation Service, 2022). The Rio Chama below Abiquiu Dam, N. Mex., sampling site (herein referred to as “Rio Chama Abiquiu”; site number 08287000) is surrounded by about 70 percent shrubland/grassland, 26 percent forested land, and 4 percent open water. Downstream from the confluence of the Rio Grande and the Rio Chama near Santa Fe, N. Mex., is the sampling site Rio Grande Buckman. The site is surrounded by 84 percent shrubland/grassland and by about 10 percent forested land. Just downstream from this site, water is pumped from the Rio Grande to a treatment plant to serve the City of Santa Fe and surrounding communities (Buckman Direct Diversion, 2015).

Samples were collected at the northern edge of New Mexico’s largest municipality, Albuquerque, at Rio Grande Alameda, and near the southern boundary of the urban area at Rio Grande Valle de Oro. Within the Middle Rio Grande Basin as well as this reach within Albuquerque, the inner valley of the Rio Grande has a system of riverside drains and irrigation canals and ditches. The irrigation canals and ditches are primarily used during irrigation season (typically mid-March through October), when water from the river is diverted by the Middle Rio Grande Conservancy District for delivery to irrigated fields (Bartolino and Cole, 2002). The riverside drains extend parallel to both sides of the river and were constructed to capture lateral groundwater flow from the river. This helps to stabilize the groundwater table to avoid waterlogging of soils near the river. These riverside drains, which also receive flow from interior drains extending across the valley to intercept seepage from canals and irrigated fields, eventually flow back to the Rio Grande (Bartolino and Cole, 2002).

Rio Grande Alameda is represented by about 80 percent shrubland/grassland and 9 percent developed land (table 3). Downstream from this sampling location, the Albuquerque Bernalillo County Water Utility Authority operates facilities constructed as part of the San Juan-Chama Drinking Water Project to provide a percentage of Albuquerque’s drinking water. The diverted water has been imported via a tunnel from tributaries of the San Juan River in the Colorado River Basin into reservoirs along the Rio Chama, which flow into the Rio Grande (Albuquerque Bernalillo County Water Utility Authority, 2022). A raw-water pump station diverts water from the Rio Grande to a treatment plant to provide drinking water for Albuquerque residents. After use, unconsumed water is directed to the wastewater treatment plant (WWTP; Albuquerque Bernalillo County Water Utility Authority, 2021). The Albuquerque WWTP is the largest treatment facility in New Mexico and discharges into the Rio Grande. Downstream from the Albuquerque WWTP is a large arroyo (132-mi^2 drainage area), which flows into the Rio Grande from the east. The arroyo serves as the primary channel for snowmelt and stormwater from areas east of Albuquerque (City of Albuquerque Parks and Recreation Department Open Space Division, 2014). Several major stormwater diversions also contribute large amounts of stormflow to the Rio Grande from major residential and commercial areas.

Rio Grande Valle de Oro is approximately 3 mi downstream from the Albuquerque WWTP. Near Rio Grande Valle de Oro, the surrounding land cover consists of about 49 percent shrubland/grassland and 40 percent developed land (table 3). Farther downstream from this site, the Rio Grande is joined by the Rio Puerco (fig. 2). The Rio Puerco watershed (table 2) of west central New Mexico includes approximately 4,834 mi of water courses that usually flow intermittently in the summer after storms. The Rio Puerco contributes a very small percentage of the Rio Grande’s flow; however, it contributes over half of the total sediment load that enters the Elephant Butte Reservoir (Natural Resources Conservation Service, 2022). The Rio Puerco near Bernardo, N. Mex. sampling site (herein referred to as “Rio Puerco Bernardo”; site number 08353000) is surrounded by 87 percent shrubland/grassland and 13 percent barren land.

Rio Grande Floodway is located about 30 mi upstream from the Elephant Butte Reservoir (fig. 2), and the surrounding land cover is composed almost exclusively of shrubland/grassland (table 3). Rio Grande El Paso is the most downstream sampling location on the Rio Grande and is more than 100 mi south of Elephant Butte Reservoir, across the New Mexico border in El Paso, Tex. Land use near this site is composed of 49 percent shrubland/grassland and almost 40 percent developed land.

The headwaters of the Pecos River are in northern New Mexico, and the river flows southward through the eastern portion of the State until it reaches the Rio Grande south of the New Mexico border (Bureau of Reclamation, 2021). Three sites were sampled along the Pecos River (fig. 2). The most upstream site is Pecos River near Puerto de Luna, N. Mex. (herein referred to as “Pecos Puerto de Luna”; site number 08383500) in the Pecos Headwaters watershed. The Pecos River flows southeast to the Upper Pecos-Long Arroyo watershed where the Pecos River near Artesia, N. Mex. sampling site (herein referred to as “Pecos Artesia”; site number 08396500) is located. The next site downstream is Pecos River at Red Bluff, N. Mex. (herein referred to as “Pecos Red Bluff”; site number 08407500) in the Upper Pecos-Black watershed. All three sites have dominantly shrubland/grassland land cover (table 3).

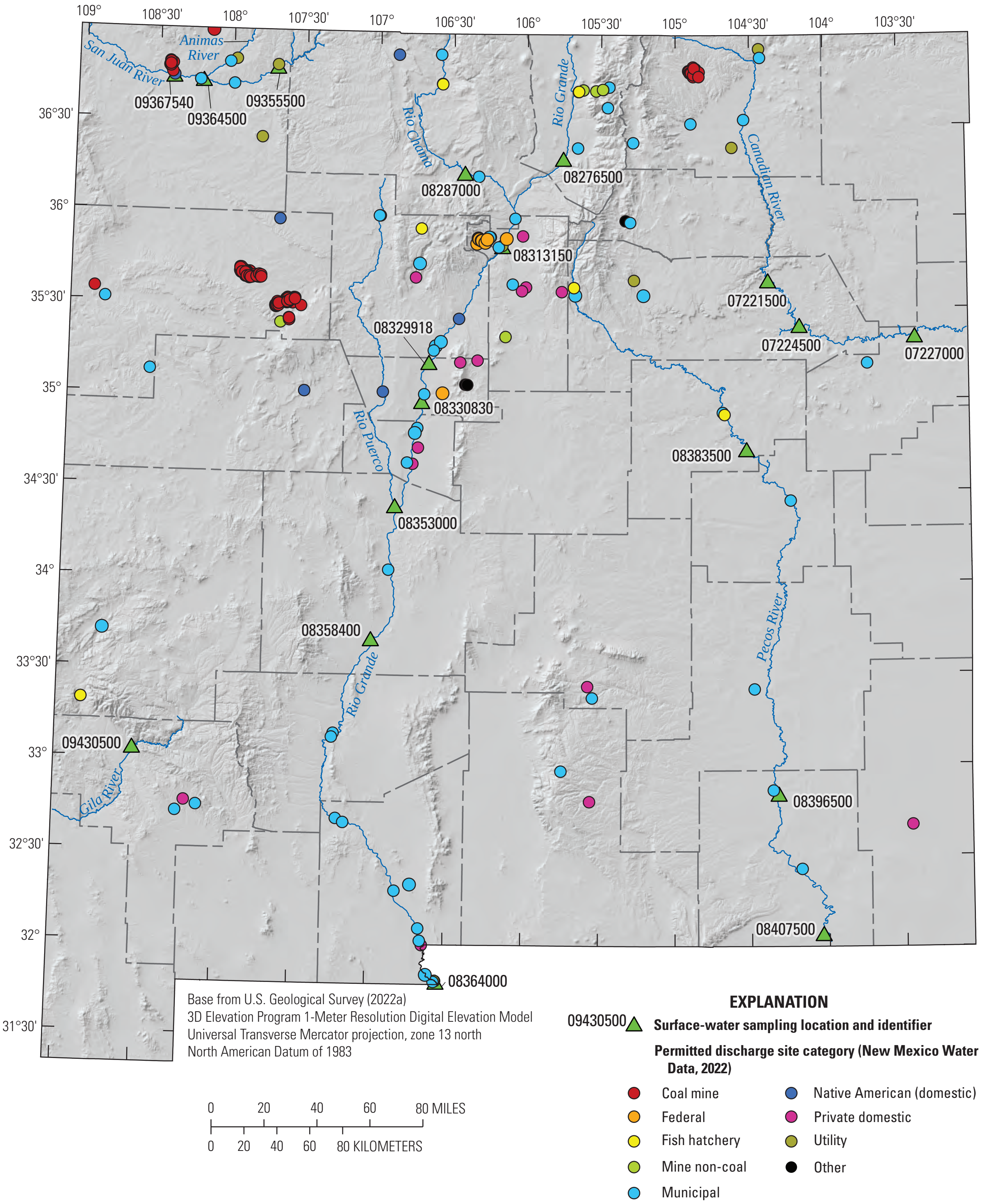
Potential Per- and Polyfluoroalkyl Substance Sources

PFAS originate from a variety of sources and are used in many industrial and consumer applications. Glüge and others (2020) identified more than 1,400 PFAS compounds and more than 200 uses of those compounds. PFAS are used in industries ranging from oil and gas extraction to electroplating to textile production. There are many other uses for PFAS, including firefighting foams, cookware, adhesives, paper, and packaging. These materials end up in landfills and landfill leachate, as well as at WWTPs (Ahrens and others, 2009; Busch and others, 2010).

The input of PFAS from WWTPs is of particular interest for surface water, as PFAS are present in both WWTP influent and effluent across the country (Lenka and others, 2021). Rice and Westerhoff (2017) evaluated the dilution factor—defined as the ratio of streamflow to treated wastewater—for the contiguous United States. Several segments of the rivers in New Mexico, including large segments of the Rio Grande, Pecos, Canadian, and San Juan Rivers, had dilution factors less than 10 and even less than the lowest classification of 2, which indicates a larger fraction of wastewater in the river.

Several National Pollutant Discharge Elimination System (NPDES) permitted discharges exist within the near-site watersheds of, and upstream from, the surface-water sites (fig. 3, table 4). NPDES permits specify limits on what can be discharged to ensure that the discharge does not impair water quality or human health, and a permit can include multiple discharge locations, also known as outfalls (EPA, 2022e). San Juan Archuleta is downstream from a utility NPDES permitted discharge. A domestic NPDES permitted discharge is upstream from San Juan Fruitland. Upstream from Pecos Artesia is a WWTP. On the Rio Grande, there are several NPDES permitted discharges. Rio Grande Taos is downstream from a WWTP with an NPDES permitted discharge. Upstream from Rio Grande Buckman, there are seven Federal NPDES permitted discharges in addition to two municipal outfalls and one private domestic NPDES permitted discharge. Upstream from Rio Grande Alameda, three WWTPs have NPDES permitted discharges. Upstream from Rio Grande Valle de Oro, the State’s largest WWTP discharges into the Rio Grande. Above Rio Grande El Paso, there are two WWTPs and two utility NPDES permitted discharges. Additionally, there are multiple permitted discharges upstream from the sites beyond the near-site watershed and those types and quantities are shown in table 5. PFAS are very persistent and resistant to degradation, and permitted discharges upstream could be relevant to PFAS occurrence at a site.

The EPA Enforcement and Compliance History Online database has compiled national PFAS datasets that can be used to evaluate PFAS in communities, including occurrence, testing, and reporting (EPA, 2022b). The datasets include PFAS manufacturers, Federal sites, facilities in industries that may be handling PFAS (for example, airports and fire training sites), NPDES discharges that are monitored for PFAS, and superfund sites with PFAS detections. From these datasets, facilities in industries that may be handling PFAS were mapped for New Mexico and selected areas of neighboring States (fig. 4). A summary of the facilities within the near-site watersheds of the surface-water sites is provided in table 6. No facilities were within 3,000 ft, which exceeds the default radius of 1,000 ft used by the NMED for wellhead protection plans (A. Jochems, NMED, written commun, 2023) of groundwater wells, springs, or diversions.



Base from U.S. Geological Survey (2022a)
3D Elevation Program 1-Meter Resolution Digital Elevation Model
Universal Transverse Mercator projection, zone 13 north
North American Datum of 1983

Figure 3. National Pollutant Discharge Elimination System permitting program discharge locations across New Mexico (New Mexico Water Data, 2022).

Table 4. National Pollutant Discharge Elimination System discharges within the near-site watershed area of study sites (New Mexico Water Data, 2022).

[USGS, U.S. Geological Survey; N. Mex., New Mexico; Tex., Texas]

USGS site number	Site name	Permit type	Number of outfalls
08276500	Rio Grande below Taos Junction Bridge near Taos, N. Mex.	Municipal	1
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	Federal	7
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	Municipal	2
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	Private domestic	1
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	Municipal	1
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	Municipal	1
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	Municipal	1
08330830	Rio Grande at Valle de Oro, N. Mex.	Municipal	1
08330830	Rio Grande at Valle de Oro, N. Mex.	Federal	1
08364000	Rio Grande at El Paso, Tex.	Municipal	1
08364000	Rio Grande at El Paso, Tex.	Utility	2
08364000	Rio Grande at El Paso, Tex.	Municipal	1
08396500	Pecos River near Artesia, N. Mex.	Municipal	1
09355500	San Juan River near Archuleta, N. Mex.	Utility	1
09367540	San Juan River near Fruitland, N. Mex.	Native American (domestic)	1

Table 5. National Pollutant Discharge Elimination System discharges upstream from the study sites and if relevant, downstream from the nearest upstream site (New Mexico Water Data, 2022).

[USGS, U.S. Geological Survey; N. Mex., New Mexico; Tex., Texas; R, river]

USGS site number	Site name	Number of outfalls upstream	Permit type (number of facilities)
07221500	Canadian River near Sanchez, N. Mex.	4	Municipal (2), utility (2)
07224500	Canadian River Below Conchas Dam, N. Mex.	0	--
07227000	Canadian River at Logan, N. Mex.	1	Municipal (1)
08287000	Rio Chama below Abiquiu Dam, N. Mex.	2	Municipal (1), fish hatchery (1)
08276500	Rio Grande below Taos Junction Bridge near Taos, N. Mex.	3	Municipal (1), fish hatchery (1), mine (noncoal) (1)
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	12	Federal (7), municipal (2), private domestic (1)
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	11	Federal (5), municipal (4), utility (1), Native American (domestic) (1)
08330830	Rio Grande at Valle De Oro, N. Mex.	3	Federal (1), municipal (1), private domestic (1)
08353000	Rio Puerco near Bernardo, N. Mex.	0	--
08358400	Rio Grande Floodway at San Marcial, N. Mex.	6	Municipal (4), domestic (2)
08364000	Rio Grande at El Paso, Tex.	13	Municipal (10), private domestic (1), utility (2)
08383500	Pecos River near Puerto De Luna, N. Mex.	5	Municipal (2), fish hatchery (2), private domestic (1)
08396500	Pecos River near Artesia, N. Mex.	3	Municipal (3)
08407500	Pecos River at Red Bluff, N. Mex.	1	Municipal (1)
09355500	San Juan River near Archuleta, N. Mex.	1	Utility (1)
09364500	Animas River at Farmington, N. Mex.	2	Municipal (1), utility (1)
09367540	San Juan R near Fruitland, N. Mex.	3	Municipal (1), Native American (domestic) (1), utility (1)
09430500	Gila River near Gila, N. Mex.	0	--

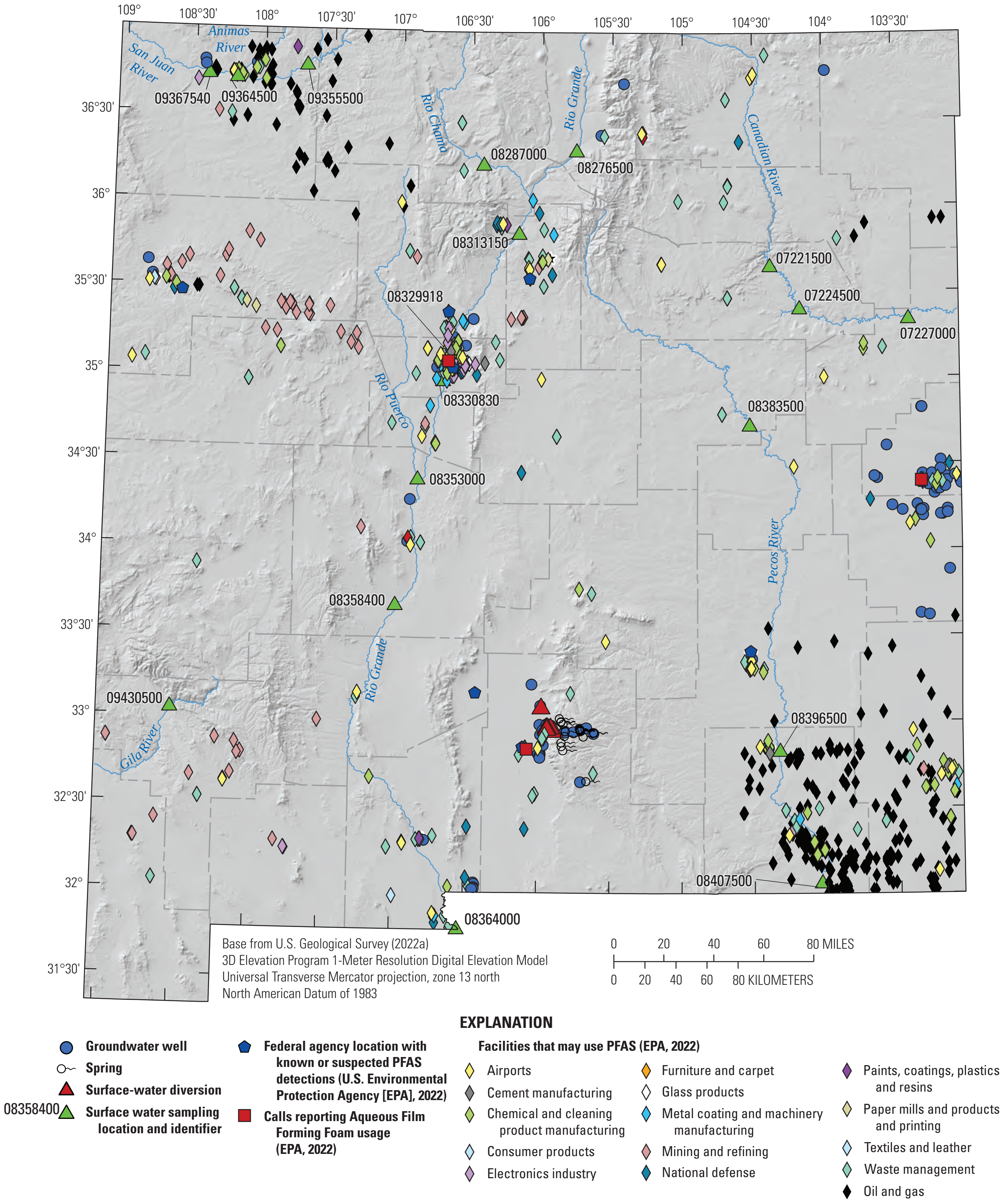


Figure 4. Locations of facilities that may use per- and polyfluoroalkyl substances (PFAS) across New Mexico (U.S. Environmental Protection Agency [EPA], 2022b).

Table 6. Number and type of facilities potentially handling per- and polyfluoroalkyl substances (PFAS) within the near-site watershed of surface-water sites (U.S. Environmental Protection Agency [EPA], 2022b).

[USGS, U.S. Geological Survey; N. Mex., New Mexico; Tex., Texas]

USGS site number	Site name	Number of facilities potentially handling PFAS
08287000	Rio Chama below Abiquiu Dam, N. Mex.	Waste management (1)
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	Airports (1), national defense (2), paints and coatings (1), waste management (1)
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	Chemical manufacturing (4), electronics industry (11), industrial gas (2), metal coating (2), metal machinery manufacturing (2), paper mills and products (1), printing (1), textiles and leather (1), waste management (9)
08330830	Rio Grande at Valle De Oro, N. Mex.	Airports (11), chemical manufacturing and cleaning product manufacturing (7), electronics industry (10), glass products (1), metal coating and metal machinery manufacturing (11), national defense (13), oil and gas (2), paints, coatings, plastics and resins (5), printing (5), waste management (5)
08364000	Rio Grande at El Paso, Tex.	Waste management (3)
08396500	Pecos River near Artesia, N. Mex.	Airports (1), chemical manufacturing (4), national defense (1), oil and gas (15)
08407500	Pecos River at Red Bluff, N. Mex.	Oil and gas (7)
09355500	San Juan River near Archuleta, N. Mex.	Oil and gas (3)
09364500	Animas River at Farmington, N. Mex.	Chemical manufacturing (3), metal coating (1), oil and gas (5), waste management (3)
09367540	San Juan River near Fruitland, N. Mex.	Oil and gas (4)

Methods

From August 2020 to October 2021, samples were collected across the State at the locations shown in figures 1 and 2. These locations were selected to cover urban, agricultural, and undeveloped areas encompassing a spectrum of anthropogenic activities. At the request of the NMED and the State legislature, this study increased focus in Curry and Otero Counties, both of which have known PFAS releases (EPA, 2022b). However, those releases were not targeted by this study. This section describes field methods for collection and analyses of water samples. Additionally, quality-control samples and data-analysis methods are discussed. Water-quality and streamflow data for sampled sites are publicly available from the USGS National Water Information System (USGS, 2022b) using the site identification numbers in tables 1 and 2. Water-quality data also are available in appendix 1, tables 1.1–1.4.

Field Methods

For most analytes, the methods described in this section for collecting groundwater and surface-water samples are documented in the USGS National Field Manual for the Collection of Water-Quality Data (USGS, variously dated). However, the USGS field manual does not currently (2022) include the methods described here for the collection of water samples for PFAS analysis because USGS standard methods have not yet been published.

Groundwater

Water samples were collected from 117 wells and 24 springs by following standard USGS protocols (USGS, variously dated) (table 1). Several sites that had detections of PFAS were resampled, and the sampling frequency at each site is indicated in table 1. Sites were resampled, when possible, if there was a PFAS detection or they were resampled to meet objectives for additional sampling in Curry and Otero Counties. Seasonal variation was not evaluated. Before water samples were collected, field properties including pH, water temperature, specific conductance, and dissolved oxygen were measured in a flow-through cell during well purging at each sampling site. All wells were pumped using dedicated pumps installed within each well by the owner, who reported discharge. Water level, casing dimensions, and pumping rate were used to calculate the purge volume and the time required to purge three casing volumes and allow field parameters to stabilize prior to sample collection. Spring discharge could not be measured because of the spring infrastructure and access. Groundwater samples were collected from a raw-water tap before any treatment by the system owner. Water samples were collected using C-flex tubing connected in line with the groundwater raw-water tap or pumped with a peristaltic pump from the spring orifice and filtered (0.45-micrometer pore size) for major cations, trace elements, alkalinity, nutrients, dissolved organic carbon (DOC), and radiocarbon. The major cations, trace element, and DOC samples were preserved to less than pH 2. Tritium, stable isotopes of water ($\delta^{18}O$ and $\delta^{2}H$), and PFAS were collected as unfiltered samples directly from the raw-water tap or directly from the spring. PFAS samples were collected directly into high density polyethylene sample bottles by USGS staff who wore nitrile gloves over elbow length polyethylene gloves during sampling. Sampling at seventeen sites—sites 21, 22, 28, 29, 31–35, 38–40, 47, 49, 52, 57, and 69—only included PFAS and stable isotopes. Nonwaterproof labels were affixed to the bottles and annotated using a writing implement other than permanent marker, which was prohibited.

Surface Water

Eighteen surface-water locations were sampled across the State (table 2), as well as six surface-water diversions. The rivers were sampled during stable flow, and stormflow events were avoided. Additionally, the frequency of sampling was dependent on the location. Some surface-water sites were sampled while sampling for other projects to minimize travel time and most efficiently use available resources. Although some sites were sampled more frequently than others, seasonality could not be captured or evaluated during this study. Before water samples were collected at a river cross section, field properties including pH, water temperature, specific conductance, and dissolved oxygen were measured from five points along the cross section at the sampling location and the median value was used, with the exception of pH, which was measured in still water from the churn. Surface-water samples were collected by using equal width increment sampling or with dip sampling for average velocities less than 1.5 feet per second, following standard USGS protocols (USGS, variously dated). A polycarbonate sample bottle and polyoxymethylene nozzle were used by USGS staff to collect each PFAS surface-water sample while wearing elbow length polyethylene gloves and nitrile gloves over the polyethylene gloves. Surface-water samples from the cross section for PFAS were then composited into a polycarbonate churn (equipment was cleaned with Liquinox, tap water, 5 percent hydrochloric acid, deionized water, methanol, and PFAS-free blank water), while wearing elbow length polyethylene gloves and nitrile gloves over the polyethylene gloves. A separate sample for wastewater tracers was collected using Teflon equipment (cleaned with Liquinox, tap water, 5 percent hydrochloric acid, deionized water, methanol, and organic-free blank water) at selected surface-water sites after processing of the sample collected using the polycarbonate equipment. Water samples were collected using C-flex tubing and filtered (0.45-micrometer pore size) for major cations, trace elements, and alkalinity. The major cation, trace element, and DOC samples were preserved to less than pH 2. DOC samples were collected directly from the centroid of the surface-water cross section because the churns used for sampling had both been rinsed with methanol. DOC samples were filtered in the laboratory. Wastewater tracers were collected as raw, unfiltered samples from the Teflon churn. PFAS were collected as raw, unfiltered samples from the polycarbonate churn directly into high density polyethylene sample bottles by USGS staff wearing elbow length polyethylene gloves and nitrile gloves over the polyethylene gloves. Nonwaterproof labels were affixed to the bottles and annotated using a writing implement other than permanent marker, as recommended by guidance for minimizing PFAS contamination during sample collection (Interstate Technology Regulatory Council, 2023).

Quality-Control Sample Collection

Quality-control samples consisted of replicate and blank samples collected using the same procedures to collect the environmental samples (USGS, variously dated). Field blanks for groundwater sites and certified PFAS-free water were poured directly into the PFAS sample bottles. Field blanks for surface-water sites were collected as described in the National Field Manual (USGS, variously dated). Field blanks were collected at several different sites and processed by different field personnel. Inorganic blanks at surface-water sites were not collected because of the use of a different type of blank water (inorganic-free blank water) that would negate the PFAS-cleaning procedures. Certified inorganic-free blank water was used for major ions, trace elements, nutrients, and DOC. Certified organic-free blank water was used for wastewater tracers, and certified organic and PFAS-free water was used for PFAS. Replicates were collected using the methods outlined in the National Field Manual (USGS, variously dated), concurrently for surface water and sequentially for groundwater. Replicate locations were chosen randomly, as it was unknown whether PFAS would be present at a given site. When possible, however, replicates were added during subsequent sampling events at sites where detections were found. Quality-control sample data are provided in appendix 1, tables 1.2 and 1.4.

Analytical Methods

Twenty-eight PFAS compounds (table 7) were analyzed in both groundwater and surface-water samples at SGS North America in Orlando, Florida, using a modified EPA 537.1 method (EPA, 2018). With this method, a sample is fortified with surrogates and passed through a solid phase extraction cartridge to extract the analytes. The compounds are then extracted from the cartridge using methanol. The extract is then concentrated and adjusted to a 1-milliliter volume, and a 10-microliter volume is analyzed using liquid chromatography with tandem mass spectrometry. The analytes are separated and identified by comparing mass spectra and retention times to reference spectra and retention times of calibration standards. Analyte concentrations are determined using internal standards (EPA, 2018). This method included 11 perfluoroalkylcarboxylic acids, 7 perfluoroalkyl sulfonic acids, 1 perfluorooctanesulfonamide, 2 perfluorooctane sulfonamidoacetic acids, 3 fluorotelomer sulfonates, and 4 next generation PFAS. The method detection level for each analyte varies with each laboratory run, which could vary if there was matrix interference, and the laboratory reported results above the laboratory detection level. The laboratory estimated concentrations that were below the reporting level (table 7) but above the detection level when the compound met criteria indicating its presence. Results below the detection level were reported as less than the reporting level.

Groundwater and Otero County Surface-Water Diversion

Water samples (including surface-water diversion samples) were analyzed for major cations, trace elements, and nutrients by the USGS National Water Quality Laboratory in Denver, Colorado. Analytical methods from the National Water Quality Laboratory included inductively coupled plasma-mass spectrometry to determine arsenic concentration (Garbarino and others, 2006). Inductively coupled plasma atomic emission spectrometry was used to analyze for cations (calcium, iron, magnesium, manganese, potassium, and sodium) (Fishman, 1993). Anions (chloride, fluoride, and sulfate) were analyzed by ion chromatography, and silicon dioxide (SiO_2) was analyzed by discrete analyzer colorimetry (Fishman and Friedman, 1989). Nitrate (NO_3) plus nitrite (NO_2) was analyzed by colorimetry (Patton and Kryskalla, 2011).

Stable isotope ratios of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) of water were measured at the USGS Reston Stable Isotope Laboratory in Reston, Virginia. Standardization is based on international reference materials, Vienna Standard Mean Ocean Water, and Standard Light Antarctic Precipitation. Reston Stable Isotope Laboratory samples were analyzed using mass spectrometry following methods by Révész and Coplen (2008a, b). The two sigma uncertainties are 0.2 parts per thousand (per mil) for oxygen and 2 per mil for hydrogen isotopic ratios reported relative to Vienna Standard Mean Ocean Water.

The University of Miami Tritium Laboratory in Miami, Florida, measured tritium in samples using the electrolytic enrichment and gas-counting method, with a reporting limit of 0.3 picocuries per liter (pCi/L; Östlund, 1987). Carbon-14 (^{14}C) and $\delta^{13}C$ (normalized ratio of carbon-13 and carbon-12) were analyzed by the National Ocean Sciences Accelerator Mass Spectrometry at the Woods Hole Oceanographic Institution, Massachusetts (Stuiver and Polach, 1977). ^{14}C was reported as absolute percent modern carbon and $\delta^{13}C$ as per mil Vienna Pee Dee Belemnite.

Surface Water

Surface-water samples were analyzed for organic chemicals (wastewater tracer compounds) at the USGS Integrated Water Chemistry Assessment Laboratory in Boulder, Colo. DOC and aqueous inorganic chemicals (trace elements, rare earth elements, and major cations and anions) were measured by the USGS Analytical Trace Element Chemistry Common Services Laboratory in Boulder, Colo. Neutral organic wastewater tracer compounds were extracted by continuous liquid-liquid extraction and measured by gas chromatography-tandem mass spectrometry in multiple monitoring mode following methods by Barber and others (2000), with quantified compound values reported above the reporting level. Surrogate standards were added prior to extraction and workup procedures, and isotopically labeled internal standards were added to the extract immediately prior to analysis. DOC samples were analyzed by platinum catalyzed persulfate/ultraviolet light oxidation with infrared detection, and ultraviolet light absorbance at 254 nanometers was measured in a 1-centimeter quartz cell (Weishaar and others, 2003). Major anions were measured by ion chromatography with conductivity detection using a Dionex Model ICS3000 ion chromatograph with suppressed conductivity detection, an IonPac AS18 analytical column with an IonPac AG18 guard column, and a 28-millimolar (mM) potassium hydroxide mobile phase (Pfaff, 1993). Metals and major cations were measured by inductively coupled plasma-optical emission spectrometry (Garbarino and Taylor, 1979). Trace elements and rare earth elements were measured by inductively coupled plasma-mass spectrometry (Garbarino and Taylor, 1996). Individual samples were analyzed in triplicate and the reporting level was determined for each batch sample run.

Surface-Water Surrogate Standard and Internal Standard Spikes

To provide robust quality assurance for wastewater tracer analysis over the gas chromatography-tandem mass spectrometry method, different surrogate standard and internal standard compounds were used. Eight surrogate standards were spiked into the sample matrix before any extraction and workup procedures in the laboratory to provide information on how much of the compound was extracted and how much was lost by any cleanup procedures. Percentage recoveries of these surrogate standards were then used to estimate and control for matrix effects and sample workup effects on targeted wastewater tracer compounds that are chemically similar. The percent recovery observed for surrogate standard spikes added to each environmental sample are available in appendix 1, table 1.4. Additionally, a mixture of six deuterated internal standards (EPA 8270 Semivolatile Internal Standard Mix) was added to each worked-up extract immediately before injection into the gas chromatography-tandem mass spectrometer to monitor and control for injection problems or drift in instrument performance.

Table 7. Per- and polyfluoroalkyl substances analyzed by modified U.S. Environmental Protection Agency 537.1 method (EPA, 2018) and the analyte abbreviations.

[Laboratory reporting levels are given in nanograms per liter]

Analyte	Analyte abbreviation	Chemical abstract service number	Minimum laboratory reporting level for groundwater	Maximum laboratory reporting level for groundwater	Minimum laboratory reporting level for surface water	Maximum laboratory reporting level for surface water
Perfluoroalkylcarboxylic acids						
Perfluorobutanoic acid	PFBA	375-22-4	3.6	9.1	3.4	19
Perfluoropentanoic acid	PFPeA	2706-90-3	1.8	11	1.7	7.1
Perfluorohexanoic acid	PFHxA	307-24-4	1.8	11	1.7	7.1
Perfluoroheptanoic acid	PFHpA	375-85-9	1.8	11	1.7	7.1
Perfluorooctanoic acid	PFOA	335-67-1	1.8	4.5	1.7	7.1
Perfluorononanoic acid	PFNA	375-95-1	1.8	4.5	1.7	7.1
Perfluorodecanoic acid	PFDA	335-76-2	1.8	4.5	1.7	7.1
Perfluoroundecanoic acid	PFUnDA	2058-94-8	1.8	4.5	1.7	11
Perfluorododecanoic acid	PFDoDA	307-55-1	1.8	9.3	1.7	36
Perfluorotridecanoic acid	PFTrDA	72629-94-8	1.8	9.3	1.7	36
Perfluorotetradecanoic acid	PFTeDA	376-06-7	1.8	10	1.7	19
Perfluoroalkyl sulfonic acids						
Perfluorobutanesulfonic acid	PFBS	375-73-5	1.8	4.5	1.7	7.1
Perfluoropentanesulfonic acid	PFPeS	2706-91-4	1.8	4.5	1.7	7.1
Perfluorohexanesulfonic acid	PFHxS	355-46-4	1.8	4.5	1.7	7.1
Perfluoroheptanesulfonic acid	PFHpS	375-92-8	1.8	4.5	1.7	7.1
Perfluorooctanesulfonic acid	PFOS	1763-23-1	1.8	4.5	1.7	7.1
Perfluorononanesulfonic acid	PFNS	474511-07-4	1.8	4.5	1.7	7.1
Perfluorodecanesulfonic acid	PFDS	335-77-3	1.8	4.5	1.7	8.9
Fluorotelomer sulfonates						
4:2 Fluorotelomer sulfonate	4:2FTS	757124-72-4	7.1	43	6.9	29
6:2 Fluorotelomer sulfonate	6:2FTS	27619-97-2	7.1	11	6.9	29
8:2 Fluorotelomer sulfonate	8:2FTS	39108-34-4	7.1	11	6.9	29
Perfluorooctane sulfonamide	PFOSA	754-91-6	3.6	5.3	3.4	23
Perfluorooctane sulfonamido acetic acids						
N-Methyl perfluorooctanesulfonamidoacetic acid	MeFOSAA	2355-31-9	3.6	9.1	3.4	23
N-Ethyl perfluorooctanesulfonamidoacetic acid	EtFOSAA	2991-50-6	3.6	9.1	3.4	23

Table 7. Per- and polyfluoroalkyl substances analyzed by modified U.S. Environmental Protection Agency 537.1 method (EPA, 2018) and the analyte abbreviations.—Continued

[Laboratory reporting levels are given in nanograms per liter]

Analyte	Analyte abbreviation	Chemical abstract service number	Minimum laboratory reporting level for groundwater	Maximum laboratory reporting level for groundwater	Minimum laboratory reporting level for surface water	Maximum laboratory reporting level for surface water
Next generation per- and polyfluoroalkyl substances						
Hexafluoropropylene oxide dimer acid (GenX)	HFPO-DA	13252-13-6	3.6	23	3.4	20
4,8-dioxa-3H-perfluorononanoic acid	ADONA	919005-14-4	7.1	11	6.9	29
9-chlorohexadecafluoro-3-oxanone-1-sulfonic acid	9Cl-PF3ONS	756426-58-1	7.1	11	6.9	29
11-chloroeicosafluoro-3-oxaundecane-1-sulfonic acid	11Cl-PF3OUdS	763051-92-9	7.1	37	6.9	140

Data Analysis

Methods for data analysis are described below to address calculations, land cover assessment, and statistical analysis.

Total Per- and Polyfluoroalkyl Substances Concentrations

The total PFAS concentration was calculated for each site listed in this report, and any individual PFAS concentrations of the 28 compounds were reported below the laboratory reporting level, with a "<" were treated as "0" values when calculating the total PFAS concentration. Additionally, when the average PFAS concentration was plotted on figures, if there were no detections of PFAS in the whole sample, the value was considered "0" when calculating the average.

Land Cover Assessment

The surface-water sites selected for this study were located at established USGS streamgaging sites. Therefore, the sites were often not at the downstream end of a watershed, and selecting a way to evaluate surrounding land cover needed to be more specific than evaluating land cover across the entire watershed a given site was located in. The surrounding land cover at surface-water sites (table 3) was determined using the methods outlined in Medalie and others (2020), which showed that glyphosate detections were correlated to near-site watershed land use more strongly than land use within the whole watershed. A 15-kilometer buffer was created around each surface-water site and then clipped to the upstream watershed using ArcGIS Pro (Esri, 2023). The most recently available land cover data (Dewitz and others, 2021) were used to determine distribution within the buffer. The land cover in each near-site watershed was then used to evaluate associations between PFAS detections and land cover. The sites were categorized into a near-site land cover category on the basis of the percentage of developed (includes a range of developed areas mixed with grass cover with some constructed materials to areas that are composed entirely of impervious surfaces), agricultural (includes pasture, hay, and cultivated crops), and undeveloped land cover (includes forests, shrublands, grasslands, open water, wetlands, and barren land) (Dewitz and others, 2021). The categories were defined with the following criteria: (1) developed, near-site watershed contained greater than 30 percent developed land cover; (2) mixed, near-site watershed contained greater than 10 percent mixed land cover (developed plus agricultural ranged from 10 to 29.9 percent); and (3) undeveloped, near-site watershed contained greater than 90 percent undeveloped land cover (table 3). The medians of total PFAS concentration were calculated by land cover category, and total PFAS concentrations for which concentrations of the 28 compounds were not detected were treated as "0" values. Additionally, when calculating the medians, the sites were put into two groups: sites that were sampled more than five times and sites that were sampled less than five times (table 2). Land cover was not evaluated for groundwater locations because of the complex flow paths of groundwater and the difficulty of delineating relevant areas contributing recharge.

Per- and Polyfluoroalkyl Substances Flux Calculations

Instantaneous loading rates, also known as flux, for PFAS in surface water were calculated using an approach of multiplying concentration times streamflow (Meals and others, 2013),

$$\text{Flux} = K \times Q \times C \qquad (1)$$

where

K is the unit conversion factor 2.4468×10^{-3} when calculating a daily loading flux in grams per day (g/d), which accounts for conversions of cubic feet to milliliters (1 cubic foot equals 28,316.8 milliliters), nanograms to grams (1×10^9 nanograms equals 1 gram), and seconds to days (86,400 seconds equals 1 day);

Q is instantaneous streamflow, in cubic feet per second; and

C is concentration, in nanograms per liter.

The instantaneous flux is the instantaneous rate at which the load passes a point in the river, converted into a daily rate. When evaluating total PFAS concentrations in this report, individual quantified PFAS concentrations were added for a total concentration; concentrations below the detection level were treated as a value of zero. This PFAS concentration calculation applies to land cover analysis, average total PFAS concentrations, PFAS proportion graphs where total PFAS concentrations are displayed, flux calculations, and other plots where total PFAS concentrations are shown.

Statistical Analysis

To help with interpretation of major- and trace-element concentrations, this large dataset was analyzed using Spearman's rank-order correlation, defined as the assessment of the increasing or decreasing relationship between the rank of each data point to assess monotonic relationships in the data. Next, principal components analysis was used to determine relationships between multiple analytes. Principal components analysis is a method of reducing the number of attributes (variables) of a large dataset while preserving both statistical information (in the form of variability) and meaningful properties of the original dataset (Jolliffe and Cadima, 2016). For the principal component analysis, new uncorrelated variables were created by solving an eigenvalue/eigenvector problem using R (version 4.2.3; R Core Team, 2023) that successively maximizes variance. Eigenvectors determine the directions of the principal component feature space, and eigenvalues determine the magnitude of the eigenvectors. The eigenvectors that correspond to the largest eigenvalues (the principal components) were then plotted as arrows overlain on the principal component analysis graph to show a reconstruction of the variance of the original data to reveal important geochemical analytes that separate the sample data into different areas of the principal component analysis graph.

Nonmetric multidimensional scaling (NMDS) is an alternative to the principal components analysis biplot described above (Helsel and others, 2020), which employs distances measured between ranks of the sample data. The NMDS method reduces the complex data structure (many samples and many elements) to represent the pairwise dissimilarity between objects in a low-dimensional space (Clarke and others, 2014, p. 5–6). The "uscore" function for R (version 4.2.3; R Core Team, 2023) from Helsel (2016) was used to compute Uscores of the data, utilizing default values to calculate the ranks of the scores (Helsel, 2012, 2016). Uscores are defined as the ranks of the sample data with lowest values having the lowest numerical rank. NMDS was performed on the uscores to compare dissimilarities within the dataset using metaMDS from the vegan package in R (Oksanen and others, 2016), utilizing Euclidean distance, where zerodist = "add" and autotransform = "false" (Helsel, 2012). Euclidean distance refers to the length of line segment between two points calculated using the Pythagorean theorem. NMDS stress values are calculated with the "metaMDS" function and reflect how well the ordination summarizes the observed distances among the samples. Values less than or equal to (≤) 0.1 are considered fair with good ordination and no real prospect of misleading interpretation; values ≤0.05 indicate good fit, and values greater than or equal to (≥) 0.2 are deemed suspect (Clarke and others, 2014, p. 5–6).

A cluster analysis was used to identify similar groups of samples by evaluating minimum differences within groups and maximum differences among groups using the "hclust" function with Euclidian distance matrix for the elements used in the NMDS analysis. A cluster analysis is defined as an analysis to assess which data points are more similar to each other, thus belonging to a group, than they are to data points in a separate group. The Calinski criterion (a measure of the variance between clusters) was applied with the "cascadeKM" function of the vegan package in R (Oksanen and others, 2016) to determine the number of clusters that maximizes the difference between clusters while minimizing the differences within clusters. The analytes used in the NMDS analysis were evaluated for correlation by calculating Kendall's tau (a measure of the relationships between ranked data) using the "cenken" function from the NADA package in R (Lee, 2017).

Interpretation of Age Tracers

Age tracers are isotopes of elements associated with water that provide information on the timing for the recharge water to enter the subsurface then undergo subsequent decay, mixing, and water-rock interactions that provide an indication of the length of time the water has been in the subsurface (also referred to as the "age" of the water). ^{14}C values, reported by National Ocean Sciences Accelerator Mass Spectrometry as absolute percent modern carbon, were denormalized using equation 5 of Plummer and others (2012) to percent modern carbon (pmc). This study did not have enough groundwater samples along a flow path from recharge to sampling location to perform detailed geochemical modeling, so NetpathXL (a spreadsheet interface to program Netpath) was used to compute corrected groundwater ages using model 11 "Revised F&G solid ex" (Parkhurst and Charlton, 2008; Han and Plummer, 2013). Groundwater age was computed using ^{14}C values of 0 pmc for carbonate rock and 100 pmc for soil CO_2, assuming $\delta^{13}C$ values of 0 per mil for carbonate and −11.5 and −21.4 per mil for soil CO_2 (Plummer and others, 2012).

The concentration of tritium in precipitation varies spatially, and in the contiguous United States, the concentration is generally lowest in the southwest region including New Mexico (Michel and others, 2018). Categorical classification groups for groundwater age were determined for the sites sampled for this study by using the measured tritium and the tritium precipitation data from Michel and others (2018) and the methods described in Lindsey and others (2019).

Normalization of Rare Earth Elements

Rare earth elements (REEs) typically follow a pattern of concentration change between elements, but some artificial processes can cause some of the REEs to be greater or less than what they would be in the natural pattern, and these differences are considered to be anomalous when the magnitude of the variation is high. Since the studies of Bau and Dulski (1996) and Bau and others (2006), a positive gadolinium (Gd) anomaly, which is related to the use of Gd-based contrast agents in magnetic resonance imaging (MRI), is now considered worldwide to be a distinctive signature of water inputs from wastewater treatment plants in areas with MRI facilities. For this study, aqueous concentrations of REEs were normalized to the North American shale composite (Gromet and others, 1984; Piper and Bau, 2013). Background concentrations of Gd ($Gd_{background}$) from geogenic sources were interpolated from a third order polynomial regression fitted to the REE distribution from lanthanum (La) through ytterbium (Yb) at each site. The background concentrations were compared with the sample concentrations to identify samples with a Gd anomaly, which is ratio of the sample Gd to the background Gd greater than 1.

Quality-Control Data Interpretation

Quality-control samples consisted of replicate and blank samples collected using the same procedures as the environmental samples (USGS, variously dated). Laboratory quality-control samples were also analyzed with the PFAS environmental samples and were within acceptable limits for data presented in this report. There were no laboratory blank detections, and spike recoveries and duplicate comparisons were within acceptable ranges for EPA Method 537.1 modified PFAS analytical methods (data not shown).

Groundwater and Surface-Water Blanks

Twenty-three groundwater field blanks were performed for groundwater sampling, including 8 inorganic field blanks and 15 PFAS field blanks. The constituents detected in inorganic groundwater field blank samples are in table 8. A suggested concentration of influence for contamination was calculated by multiplying the maximum blank concentration by 10. The percentage of environmental samples with concentrations below this threshold represents the portion of samples for which concentrations may represent at least a 10-percent contribution from contamination bias. The samples below this threshold are, therefore, most likely to be impacted by high bias resulting from contamination sources in the field or laboratory.

Nineteen surface-water field blanks were collected, including 12 PFAS field blanks, and 4 wastewater tracer and DOC field blanks (table 9). Only one PFAS field blank had a detection. PFOS was detected below the reporting level but above the detection level at 1.1 ng/L at Rio Grande El Paso on August 25, 2020. Major ion and trace element blanks were not collected because the inorganic blank water is not certified as being free of PFAS, rendering it incompatible with passing through the sampling equipment prior to collecting PFAS samples. No DOC was detected in the surface-water blanks.

Five wastewater tracer compounds were present above the method detection level in the field blanks (4-t-OP2EO, 4-t-OP3EO, 5-methyl-1H-benzotriazole, 2,6-di-*tert*-butyl-1,4-benzoquinone, and cholesterol) (table 9). The aforementioned compounds were also present in the corresponding lab blank, with the exception of 5-methyl-1H-benzotriazole. Thus, study reporting levels (SRLs) were established for these five compounds: 4-t-OP2EO (SRL of 0.176 microgram per liter [μg/L]), 4-t-OP3EO (SRL of 0.191 μg/L), cholesterol (SRL of 1.36 μg/L), 2,6-di-*tert*-butyl-1,4-benzoquinone (SRL of 4.58 μg/L), and 5-methyl-1H-benzotriazole (SRL of 0.398 μg/L), with the new SRL raised to be equal to two times the highest concentration found in blank samples. Only cholesterol (Rio Chama Abiquiu, February 22, 2021, and Pecos Artesia, June 10, 2021), 2,6-di-*tert*-butyl-1,4-benzoquinone (Pecos Artesia, June 21, 2020), and 5-methyl-1H-benzotriazole (Rio Chama Abiquiu, August 13, 2020) had environmental sample values greater than the SRL.

Groundwater Replicates

Eighteen replicates of the full analytical suite, including major ions, trace elements, nutrients, DOC, stable isotopes, groundwater age dating (reduced to 11 ^{14}C and 17 tritium samples), and PFAS, were collected for this study. Four additional replicates included only PFAS, and one replicate had both stable isotopes and PFAS.

Table 8. Blank sample data for major ions and trace elements in groundwater samples.

[<, less than; mg/L, milligram per liter; μg/L, microgram per liter]

Analyte	Number of blanks	Number of blanks with a value greater than the laboratory detection level	Concentration range of blanks	Concentration for threshold of influence	Units	Percentage of environmental samples below threshold
Ammonia	8	1	<0.01–0.01	0.10	mg/L	3.0
Dissolved organic carbon	8	2	<0.23–0.36	3.63	mg/L	84.3
Arsenic	8	1	<0.1–0.16	1.61	μg/L	61.6
Copper	8	1	<0.4–1.26	12.61	μg/L	63.0
Lead	8	1	<0.02–0.03	0.26	μg/L	65.2
Molybdenum	8	1	<0.05–0.30	2.91	μg/L	74.6
Nickel	8	3	<0.2–0.41	4.10	μg/L	39.1
Antimony	8	1	<0.06–1.76	1.76	μg/L	14.5
Aluminum	8	1	<3–6.21	62.12	μg/L	0.7
Uranium	8	1	<0.03–0.22	2.20	μg/L	63.0

Table 9. Blank sample data for wastewater tracers in surface water.

[Dates are shown as month, day, year. Times shown in 24-hour format. Values are reported in micrograms per liter. env, environmental sample; blank, blank sample; <, less than; NA, not available]

Analyte	Site name, sample date, and time									
	Rio Grande Buckman, 8–28–20, (1300)		Rio Grande Alameda, 9–16–20, (1100)		San Juan Archuleta, 9–22–20, (1430)		Animas Farmington, 9–23–20, (1700)		Laboratory blank, 9–3–21	
	Env	Blank	Env	Blank	Env	Blank	Env	Blank	Env	Blank
4-t-OP2EO	<0.08	0.0813	<0.08	0.0492	<0.08	0.0390	<0.08	0.0378	NA	0.0881
4-t-OP3EO	0.1063	<0.05	0.0501	0.0481	0.0620	0.0232	0.0454	0.0331	NA	0.0956
Cholesterol	0.6045	0.3887	0.6439	0.1609	0.9218	0.1768	0.9652	0.1879	NA	0.6806
2,6-di-*tert*-butyl-1,4-benzoquinone	4.4808	1.7500	4.1610	0.5183	0.0976	0.5009	0.8150	0.5175	NA	2.2926
5-methyl-1H-benzotriazole	<0.10	0.1989	<0.10	0.0733	<0.10	0.0475	0.0967	0.0565	NA	<0.10

Variability in analyte concentration was calculated for replicate pairs using the bias-corrected log-log regression model (Mueller and others, 2015), which is based on the approximately linear relation of logarithms of standard deviation and mean concentration of replicate pairs. This linear relation can be expressed as

$$\log SD = B_0 + B_1 \log C, \tag{2}$$

where

$\log SD$ is the logarithm of replicate standard deviation;

B_0 is the intercept of the regression line, estimated by least squares;

B_1 is the slope of the regression line, estimated by least squares; and

$\log C$ is the logarithm of mean replicate concentration.

Standard deviation residuals from equation 2 are then transformed back to their original units. The mean of the transformed standard deviation residuals is the bias-correction factor, which is multiplied by the estimated standard deviations of the replicates for each analyte to express the modeled standard deviation (SD_M):

$$SD_M = bcf\{10^{[B_0+B_1 log(C)]}\}. \tag{3}$$

Equations of variability in concentration for analytes with 10 or more replicate pairs having detections are shown in table 10. Some analytes had a majority of values that were censored, and their variability could not be quantified.

A confidence interval indicating the uncertainty for a measured concentration can be calculated with the following equation (Mueller and others, 2015):

$$[C_L, C_U] = C \pm Z_{1-\alpha/2} SD, \tag{4}$$

where

C_L, C_U are the lower and upper limits of concentration for the 100(1–α/2)-percent confidence interval;

Table 10. Summary of data and results for replicate groundwater samples used in estimating variability in concentration.

[The variability equation solution gives the modeled standard deviation value based on equation 3. Replicate pairs with at least one sample having a result less than the laboratory detection level were not included in the calculation of variability equations. mg/L, milligram per liter; C, mean replicate concentration; ^, 10 raised to the power of the value in the bracket equation following the symbol; µg/L, microgram per liter]

Analyte	Units	Environmental sample range	Number of replicate pairs	Variability equation
Nitrate as nitrogen	mg/L	0.055–23.9	15	1.633{10^[−1.8792+0.369log(C)]}
Alkalinity as calcium carbonate	mg/L	50.1–2,000	16	1.344{10^[0.6822−0.256log(C)]}
Arsenic	µg/L	0.10–41.7	14	2.386{10^[−1.9342+0.570log(C)]}
Barium	µg/L	8.6–547	16	1.558{10^[−3.0338+1.528log(C)]}
Boron	µg/L	8–1376	16	1.345{10^[−1.8637+0.917log(C)]}
Calcium	mg/L	3.68–482	16	2.031{10^[−2.3038+0.950log(C)]}
Chloride	mg/L	3.05–5730	16	2.011{10^[−2.2524+0.633log(C)]}
Dissolved solids (dried at 180 degrees Celsius)	mg/L	165–58,100	16	1.275{10^[−3.5143+1.601log(C)]}
Fluoride	mg/L	0.08–2.97	15	1.459{10^[−2.1278+0.777log(C)]}
Lead	µg/L	0.02–3.83	11	1.649{10^−1.0944+1.165log(C)]}
Magnesium	mg/L	0.592–1,300	16	1.617{10^[−1.2995+0.410log(C)]}
Manganese	µg/L	0.2–459	11	1.211{10^[−1.2376+0.694log(C)]}
Molybdenum	µg/L	0.128–29.5	17	1.522{10^[−2.0266+0.497log(C)]}
Organic carbon	mg/L	0.23–21.9	16	1.423{10^[−1.5116+0.587log(C)]}
Potassium	mg/L	0.4–18.5	14	1.737{10^[−1.6464+0.402log(C)]}
Selenium	µg/L	0.12–44.4	14	2.038{10^[−1.5806+0.054log(C)]}
Sodium	mg/L	4.57–16600	16	2.453{10^[−2.5135+1.054log(C)]}
Sulfate	mg/L	8.14–33,800	16	2.243{10^[−4.1000+1.692log(C)]}
Uranium	µg/L	0.09–214	16	1.634{10^[−2.7665+1.812log(C)]}
Vanadium	µg/L	0.6–61.9	10	1.727{10^[−0.6774−0.337log(C)]}
Zinc	µg/L	2–1,900	14	1.565{10^[−0.8531+0.787log(C)]}

Z is the percentage point of the standard normal curve that contains an area of $100(1–\alpha/2)$ percent;

α is the probability that the confidence interval does not include the true concentration; and

SD is the standard deviation of the measured concentration, independently estimated from replicate variability, as determined for this study using the bias-corrected log-log regression model described above.

For example, if a sample had an arsenic concentration of 9.7 µg/L, the modeled standard deviation from equation 3 would be 0.1 µg/L. The Z value for a 95-percent confidence interval ($\alpha/2=0.025$) is 1.960, and the confidence interval from equation 4 would be

$$[C_L, C_U] = 9.7 \pm 1.960\ (0.1) = [9.5, 9.9],$$

indicating that the true value of the sample did not exceed the regulatory threshold of 10 µg/L with 95-percent confidence.

PFAS concentrations were below the laboratory detection level for the majority of 22 replicate pairs collected. Six samples had detections for a selected group of PFAS in both replicate samples (table 11). Because there were few replicate pairs, relative percent difference (RPD) was used to evaluate the replicate pairs (Mueller and others, 2015). RPD is calculated using the following equation:

$$RPD = 100\left\{\frac{\textit{larger result} - \textit{smaller result}}{(\textit{larger result} + \textit{smaller result})/2}\right\}. \quad (5)$$

The RPDs for replicate pairs for PFAS in groundwater are shown in table 11 and did not exceed 20.7 percent, which was determined to be acceptable for this study.

Surface-Water Replicates

The variability for some PFAS concentrations was higher in four surface-water replicates compared with groundwater replicates, which may reflect higher variability in the surface-water matrix than in groundwater. PFAS values were all less than the detection level for one other surface-water replicate (appendix 1, table 1.4) and variability was not able to be quantified. PFBS, perfluorodecanoic acid (PFDA), PFOS, and PFPeA were found to have RPDs greater than 20 percent in at least one replicate pair (table 12). Three of these replicate pairs with high variability had concentrations below the laboratory reporting level and above the laboratory detection level, which are known to be associated with higher analytical variability. However, given that two of four of these pairs with high variability are between results that were below the reporting level, they are actually consistent in both reporting below the reporting level. This replicate variability indicates that for surface-water sampling, low level detections have higher variability, and the higher level detections have less variability.

Four surface-water replicate samples were collected for wastewater tracers and three of these also included DOC, trace elements, and REEs (tables 13 and 14). Cholesterol, coprostanol, 2,6-di-*tert*-butyl-1,4-benzoquinone, and 5-methyl-1H-benzotriazole all had RPDs of greater than 20 percent in at least one replicate pair (table 13). The RPDs for concentrations of wastewater tracer compounds in replicate samples ranged from 2.6 to 25.6 percent for all compounds, except for 5-methyl-1H-benzotriazole (37.2 percent) and 2,6-di-*tert*-butyl-1,4-benzoquinone (46.7–162.7 percent, with an average RPD of 108 percent). These high variabilities between replicate results were not observed at concentrations near the reporting level, below which values are more highly variable, except for coprostanol, whose reporting level was 0.10 µg/L. Concentrations measured for 2,6-di-*tert*-butyl-1,4-benzoquinone are qualified as being estimated values with high uncertainty because of this high variability observed in replicate samples and the occurrence in blank samples. Additionally, although high RPDs were observed for 5-methyl-1H-benzotriazole and 2,6-di-*tert*-butyl-1,4-benzoquinone, these compounds were not reported in the environmental samples after censoring with the SRL.

Trace element RPDs are reported in table 14 and ranged from less than 1.0 to 88.5 percent and most detections were less than 1.0 µg/L. For elements that had higher concentrations (in the tens to hundreds, such as barium, boron, bromine, calcium, lithium, magnesium, sodium, strontium, sulfur, uranium, and vanadium), RPDs were largely less than 20 percent, except for aluminum, boron, iron, and silica which had RPDs exceeding 20 percent for at least one replicate. The RPD for DOC replicates was 1.4 and 13.3 percent.

Surface-Water Surrogate Recovery

Surrogates are artificial compounds similar to target analytes added to a sample prior to analysis to assess how much of the compound is detected versus what was added to understand the performance of the method. Surrogate performance was associated with wastewater tracer analysis for each sample. Surrogate recoveries for wastewater tracer analysis are generally considered to be acceptable, as determined by the analytical laboratory (Furlong and others, 2008), if within 30–150 percent. Table 15 and table 1.3 in appendix 1 list the surrogate recovery performance for surface-water environmental samples. Some samples had low surrogate recovery values, especially for compounds associated with d21 2,6-di-*tert*-butyl-4-methylphenol surrogate, and only one sample from Pecos Artesia from September 2020 had a surrogate recovery greater than 150 percent (table 15). Wastewater tracer results may underrepresent true concentrations for samples with low surrogate recovery performance.

Table 11. Replicate pairs with per- and polyfluoroalkyl substances detections and associated variability in groundwater samples.

[Dates shown as month, day, year. Time shown in 24-hour format. Values are reported in nanograms per liter. Values in italics represent estimated concentrations greater than the laboratory detection level and less than the laboratory reporting level in effect at the time of sample analysis. Env, environmental sample; Rep, replicate sample; RPD, relative percent difference; --, below the laboratory detection level; NC, not calculated]

Analyte	Report number, sample date, and time																	
	Site 25 1–12–21 (1230)			Site 44 2–9–21 (1215)			Site 18 1–13–21 (1250)			Site 18 10–15–21 (0905)			Site 54 8–26–20 (1300)			Site 140 9–29–20 (0900)		
	Env	Rep	RPD	Env	Rep	RPD	Env	Rep	RPD	Env	Rep	RPD	Env	Rep	RPD	Env	Rep	RPD
PFBA	7.4	7.7	4.0	19	17.1	10.5	--	--	NC	--	--	NC	--	--	NC	--	--	NC
PFBS	6.5	6.7	3.0	32.4	28.7	12.1	--	--	NC	--	--	NC	--	--	NC	--	--	NC
PFHxA	10.3	11.2	8.4	9	8.2	9.3	2.6	2.4	8	2.6	2.4	8	--	--	NC	--	--	NC
PFHxS	2.9	2.6	10.9	--	--	NC	--	--	NC	--	--	NC	--	--	NC	--	--	NC
PFOS	--	--	NC	--	--	NC	--	--	NC	--	--	NC	*1.3*	*1.6*	20.7	*1.8*	2	10.5
PFPeA	12.9	14	8.2	19.9	18.4	7.8	4.4	4.2	4.6	4.4	4.2	4.6	--	--	NC	--	--	NC
PFPeS	*1.5*	*1.7*	12.5	--	--	NC	--	--	NC	--	--	NC	--	--	NC	--	--	NC

Table 12. Replicate sample data and associated variability in concentration for per- and polyfluoroalkyl substances in surface-water samples for replicates with quantified values of per- and polyfluoroalkyl substances.

[Dates shown as month, day, year. Time shown in 24-hour format. Values are reported in nanograms per liter. Values in italics represent estimated concentrations greater than the laboratory detection level and less than the laboratory reporting level in effect at the time of sample analysis. Env, environmental sample; Rep, replicate sample; RPD, relative percent difference; NC, not calculated; --, below the laboratory detection level; <, less than]

Analyte	Site name, sample date, and time											
	Rio Puerco Bernardo 9–13–20 (1805)			Pecos Artesia 9–16–20 (1030)			Rio Grande Valle de Oro 7–21–21 (1600)			Rio Grande Buckman 9–17–21 (1200)		
	Env	Rep	RPD	Env	Rep	RPD	Env	Rep	RPD	Env	Rep	RPD
PFBA	23.9	24.7	3.3	*3.5*	*3.6*	2.8	8.8	9	2.2	--	--	NC
PFBS	*2.3*	*2.2*	4.4	*1.3*	*1.8*	32.2	--	--	NC	2.3	2.5	8.3
PFDA	--	--	NC	--	--	NC	*1.6*	*1.3*	20.7	--	--	NC
PFHpA	*1.8*	*1.9*	5.4	<2	*1*	NC	*1.9*	2.2	14.6	--	--	NC
PFHxA	*1.4*	*1.4*	0	--	--	NC	8.5	10.1	17.2	--	--	NC
PFNA	--	--	NC	--	--	NC	3	2.7	10.5	--	--	NC
PFOA	--	--	NC	--	--	NC	5.5	6.1	10.3	--	--	NC
PFOS	3.1	5.6	57.5	<2	*1.2*	NC	4.2	4	4.9	--	--	NC
PFPeA	3.2	*2.4*	28.6	*1*	*1.8*	57.1	19.6	17.7	10.2	--	--	NC

Table 13. Replicate sample data and associated variability in concentration for wastewater tracers in surface-water samples.

[Dates shown as month, day, year. Time shown in 24-hour format. Values are reported in micrograms per liter. Env, environmental sample; Rep, replicate sample; RPD, relative percent difference; <, less than; NC, not calculated]

Analyte	Site name, sample date, and time											
	Pecos Artesia 9–16–20 (1030)			Rio Grande Buckman 9–17–20 (1200)			Pecos Artesia 6–10–21 (0900)			Rio Grande Buckman 9–2–21 (0930)		
	Env	Rep	RPD	Env	Rep	RPD	Env	Rep	RPD	Env	Rep	RPD
Carbamazepine	<0.027	<0.027	NC	<0.027	<0.027	NC	<0.027	<0.027	NC	<0.027	<0.027	NC
Triclosan	<0.027	<0.027	NC	<0.027	<0.027	NC	<0.027	<0.027	NC	0.1598	<0.027	NC
4-NP2EO	0.3031	<0.25	NC	<0.25	<0.25	NC	0.3602	0.3197	11.9	<0.25	<0.25	NC
4-*t*-OP1EO	0.0092	<0.01	NC	<0.01	<0.01	NC	<0.01	<0.01	NC	<0.01	<0.01	NC
4-*t*-OP3EO	0.0852	0.0725	16.1	0.0501	0.0509	1.6	0.0729	0.0701	3.9	0.0621	0.0588	5.5
Cholesterol	0.8693	0.8084	7.3	0.5512	<0.25	NC	1.8368	1.7765	3.3	0.9623	1.1882	21.0
Coprostanol	<0.10	0.1326	NC	<0.10	<0.10	NC	<0.10	<0.10	NC	0.1377	0.1782	25.6
Bisphenol A	0.0302	0.0310	2.6	<0.027	0.0221	NC	0.0286	<0.027	NC	0.0589	<0.027	NC
2,6-di-*tert*-butyl-1,4-benzoquinone	0.1294	0.2952	78.1	0.9503	0.0976	162.7	0.1798	0.2894	46.7	1.1477	7.2281	145.2
3,4-Dichloroaniline	0.0476	<0.027	NC	<0.027	<0.027	NC	<0.027	<0.027	NC	<0.027	<0.027	NC
5-methyl-1H-benzotriazole	0.2234	0.3255	37.2	<0.01	<0.01	NC	<0.01	<0.01	NC	<0.01	<0.01	NC
N,N-diethyl-meta-toluamide (DEET)	<0.027	<0.027	NC	<0.027	<0.027	NC	<0.027	<0.027	NC	0.0604	<0.027	NC

Table 14. Replicate sample data and associated variability in concentration for trace elements, rare earth elements, and dissolved organic carbon in surface-water samples.

[Dates shown as month, day, year. Time shown in 24-hour format. Env, environmental sample; Rep, replicate sample; RPD, relative percent difference; µg/L, microgram per liter; <, less than; NC, not calculated; mg/L, milligram per liter; NA, not available]

Analyte	Units	Site name, sample date, and time								
		Pecos Artesia 9–16–20 (1030)			Rio Grande Buckman 9–17–20 (1200)			Rio Grande Buckman 9–2–21 (0930)		
		Env	Rep	RPD	Env	Rep	RPD	Env	Rep	RPD
Aluminum	µg/L	<1	<1	NC	16	12	31.6	8.2	6	32
Antimony	µg/L	0.19	0.2	5.9	0.16	0.16	3.2	0.13	0.13	0.8
Arsenic	µg/L	0.61	0.39	45.1	1.9	1.9	0.3	2.6	2.7	3
Barium	µg/L	27	28	4.8	68	68	0.9	84	84	0.2
Beryllium	µg/L	0.0029	0.0034	15.8	0.0026	0.0024	7.7	0.0029	0.0027	6.1
Bismuth	µg/L	<0.006	0.011	NC	<0.006	0.008	NC	<0.0010	0.0027	NC
Boron	µg/L	147	144	1.8	29	23	22.1	38	36	6.2
Bromine	µg/L	204	201	1.4	39	38	3.2	30	30	0.9
Cadmium	µg/L	0.007	0.008	12.9	0.008	0.009	11.9	0.37	0.39	2.9
Calcium	mg/L	273	266	2.7	36	31	12.5	39	40	2.2
Cerium	µg/L	0.0047	0.0048	2	0.16	0.13	23	0.099	0.093	5.7
Chromium	µg/L	<0.2	<0.2	NC	<0.2	<0.2	NC	0.3	0.2	39.8
Cobalt	µg/L	<0.002	<0.002	NC	0.09	0.063	36.4	0.1	0.093	10.9
Copper	µg/L	0.67	0.64	5.1	1.1	1	9.5	1.2	1.1	10.1
Dissolved organic carbon	mg/L	0.8	0.7	13.3	2.9	NA	NC	2.21	2.18	1.4
Dysprosium	µg/L	0.0008	0.0007	23.6	0.0097	0.0074	26.4	0.011	0.011	0.7
Erbium	µg/L	0.0008	0.0006	16.6	0.0048	0.004	19.2	0.0062	0.0055	11.5
Europium	µg/L	0.0082	0.0073	11	0.022	0.021	2	0.014	0.013	9.7
Gadolinium	µg/L	0.0018	0.0017	6.6	0.015	0.013	16.5	0.013	0.012	8.4
Gallium	µg/L	<0.0005	<0.0005	NC	0.0098	0.0081	18.5	0.0087	0.0089	1.6
Holmium	µg/L	0.0002	0.00014	35.1	0.0017	0.0013	23.6	0.0019	0.002	6.2
Iron	µg/L	1.7	2.9	51.4	16	12	23.9	7	6	16.5
Lanthanum	µg/L	0.003	0.0027	11.6	0.076	0.061	20.8	0.063	0.057	10.7
Led	µg/L	0.012	0.014	18.4	0.026	0.021	20.8	0.031	0.024	23.2
Lithium	µg/L	31	30	3.3	12	12	1	15	15	0.1
Lutetium	µg/L	<0.0001	<0.0001	NC	0.0006	0.0005	22.3	0.0008	0.0008	4.5
Magnesium	mg/L	61	60	2.2	6.1	6.2	1.5	6.6	6.7	2.5
Manganese	µg/L	1.5	1.5	0.3	2.1	1.9	8.5	0.99	0.92	6.6

Table 14. Replicate sample data and associated variability in concentration for trace elements, rare earth elements, and dissolved organic carbon in surface-water samples.—Continued

[Dates shown as month, day, year. Time shown in 24-hour format. Env, environmental sample; Rep, replicate sample; RPD, relative percent difference; µg/L, microgram per liter; <, less than; NC, not calculated; mg/L, milligram per liter; NA, not available]

Analyte	Units	Site name, sample date, and time								
		Pecos Artesia 9–16–20 (1030)			Rio Grande Buckman 9–17–20 (1200)			Rio Grande Buckman 9–2–21 (0930)		
		Env	Rep	RPD	Env	Rep	RPD	Env	Rep	RPD
Molybdenum	µg/L	2.3	2.3	0.4	4.1	4.1	0.8	7.9	8	1.6
Neodymium	µg/L	0.0025	0.0023	10.9	0.085	0.065	27.2	0.066	0.062	6.3
Nickel	µg/L	2.4	2.2	7	0.95	0.92	3.4	0.53	0.52	0.7
Phosphorus	µg/L	<2	<2	NC	4	4	7.6	13	13	1.8
Potassium	mg/L	4.5	4.5	0.2	2	2	1.8	2.8	2.8	2.4
Praseodymium	µg/L	0.0006	0.00057	3.9	0.021	0.017	20.1	0.016	0.016	2
Rubidium	µg/L	1.1	1.1	0.9	1.3	1.3	1.9	1.7	1.7	1.4
Samarium	µg/L	0.0013	0.001	23	0.016	0.013	21.8	0.013	0.013	4.2
Selenium	µg/L	1.9	1.7	10.4	0.5	0.4	7.2	0.37	0.38	4.1
Silica as SiO_2	mg/L	7	7	0.7	21	16	29.8	19	19	0.2
Silver	µg/L	<0.1	0.2	NC	<0.1	<0.1	NC	0.06	0.04	33.3
Sodium	mg/L	258	254	1.6	16	15	1.9	19	19	2.4
Strontium	µg/L	NA	NA	NC	280	273	2.4	334	335	0.2
Sulfur	mg/L	262	264	0.7	20	17	16.1	17	18	0.5
Terbium	µg/L	0.00012	0.00016	27.3	0.0017	0.0015	10.2	0.0017	0.0018	5.7
Thallium	µg/L	0.005	0.004	27.8	0.006	0.005	17.8	0.0038	0.0035	8.1
Thulium	µg/L	<0.0001	0.0002	NC	0.0006	0.0004	25.1	0.0008	0.0008	0.9
Tin	µg/L	<0.02	<0.02	NC	<0.02	<0.02	NC	0.012	0.005	88.5
Titanium	µg/L	<0.03	<0.03	NC	<0.03	<0.03	NC	0.64	0.54	17.3
Tungsten	µg/L	NA	NA	NA	NA	NA	NC	0.7	0.69	0.3
Uranium	µg/L	4.7	4.8	3	1.3	1.3	1	2.2	2.2	0.3
Vanadium	µg/L	<0.06	<0.06	NC	3.6	3.6	1.1	4.9	4.9	0.8
Ytterbium	µg/L	0.0005	0.0006	31.8	0.0037	0.0031	19.2	0.0045	0.0042	6.1
Yttrium	µg/L	0.034	0.033	3	0.055	0.047	14.3	0.061	0.059	3.6
Zinc	µg/L	0.9	0.8	8.3	0.3	0.5	46.6	<0.03	<0.03	NC

Table 15. Surrogate recovery data associated with wastewater tracer data from surface-water sample collected at Pecos Artesia in September 2020.

[%, percent]

Surrogate	Compounds associated with surrogate	Number of environmental samples outside 30–150% recovery[1]	Range of surrogate recoveries	Average of surrogate recoveries
d21 2,6-di-*tert*-butyl-4-methylphenol	2[3]-*tert*-butyl-methoxyphenol, 4-*tert*-butylphenol, 2,6-di-*tert*-butyl-1,4-benzoquinone, 2,6-di-*tert*-butyl-4-methylphenol, 2,6-di-*tert*-butylphenol, 1,2-dichlorobenzene, 1,3-dichlorobenzene, 1,4-dichlorobenzene, 4-ethylphenol, 4-methylphenol, 4-*tert*-pentylphenol, 4-propylphenol	13	1.9–99.5	35.1
d5 atrazine	Tonalide, atrazine, caffeine, cotinine, 3,4-dichloroaniline, desethylatrazine, N,N-diethyl-meta-toluamide (DEET), galaxolide, 5-methyl-1H-benzotriazole	2	6.1–124.0	78.4
4-normal-nonylphenol	4-nonylphenol, 4-normal-octylphenol, 4-*tert*-octylphenol	1	26.2–133.0	79.7
d3 triclosan	Carbamazepine, diphenhydramine, triclosan	4	0.3–107.0	68.3
4-n-NP1EO	4-NP1EO, 4-t-OP1EO	0	31.8–117.6	83.8
d6 bisphenol A	Bisphenol A	[1]1	40.1–154.1	84.3
4-*n*-NP2EO	4-NP2EO, 4-t-OP2EO, 4-t-OP3EO, 4-t-OP4EO, 4-t-OP5EO	0	35.9–114.5	81.0
d7 cholesterol	Cholesterol, coprostanol	3	21.8–106.1	45.8

[1] Surrogate recovery less than 30% for all listed numbers except for one sample with d6 bisphenol A recovery greater than 150%.

Aqueous Chemistry

Groundwater and surface-water chemistry are discussed separately given the differences in analytes and in the sources and evolutionary paths of the water.

Groundwater

This discussion of groundwater chemistry, including samples from springs, addresses PFAS results first, followed by results for general chemistry, major ions and trace elements, dissolved organic carbon, nutrients, stable isotopes, and groundwater age tracers (all results are provided in appendix 1, table 1.1, and in U.S. Geological Survey [2022b]). The public water supply systems from across New Mexico that are represented in this dataset include systems located in large urban areas, as well as systems in rural and agricultural areas. Focused sampling occurred in Curry and Otero Counties, where almost all public water supply sources were sampled.

Per- and Polyfluoroalkyl Substances

The majority of the groundwater samples from 141 groundwater sampling sites in this study did not have any detections of PFAS (fig. 5); that is, concentrations were reported by the laboratory as being below the laboratory detection level. Twenty-seven sites had PFAS detected at one or more sampling events. Fourteen sites only had one PFAS present above the laboratory detection level (table 16), 7 sites had two PFAS detected, and 7 other sites had more than two PFAS detected. Some sites were resampled if PFAS were detected. If a site was resampled, a ".1" was added to the report identification number to indicate the first sampling event and a ".2" for the second sampling event, and so on (table 16). Total PFAS concentrations ranged from 0.91 (site 136) to 80.3 ng/L (site 44, second sampling). The most frequently detected PFAS at groundwater sites were PFBS (11 sites), PFPeA (10 sites), and PFHxA (9 sites). The High Plains aquifer had a higher sample density compared to other aquifers in the study, representing 51 of the total groundwater sites, and had detections at 13 of the sites.

Some sites were sampled more than once over the course of the study. Generally, any detected PFAS and reported concentrations were similar over time at a given site. The signature of the PFAS detected (PFBA, PFPeA, PFHxA, and PFBS) was consistent over time for site 44 (figs. 1 and 5), which was sampled three times between December 2020 and June 2021 (fig. 6*A*). Variability in the PFAS concentrations over time was within the 12-percent variability from replicate samples in this study. Site 18 had two compounds—PFPeA and PFHxA—detected during each of three sampling events between September 2020 and October 2021 (fig. 6*B*). Three separate sites in a similar geographic area within Curry County—sites 25, 26, and 64—had multiple PFAS detected, with PFBS and perfluorohexanesulfonic acid (PFHxS) present at all three and

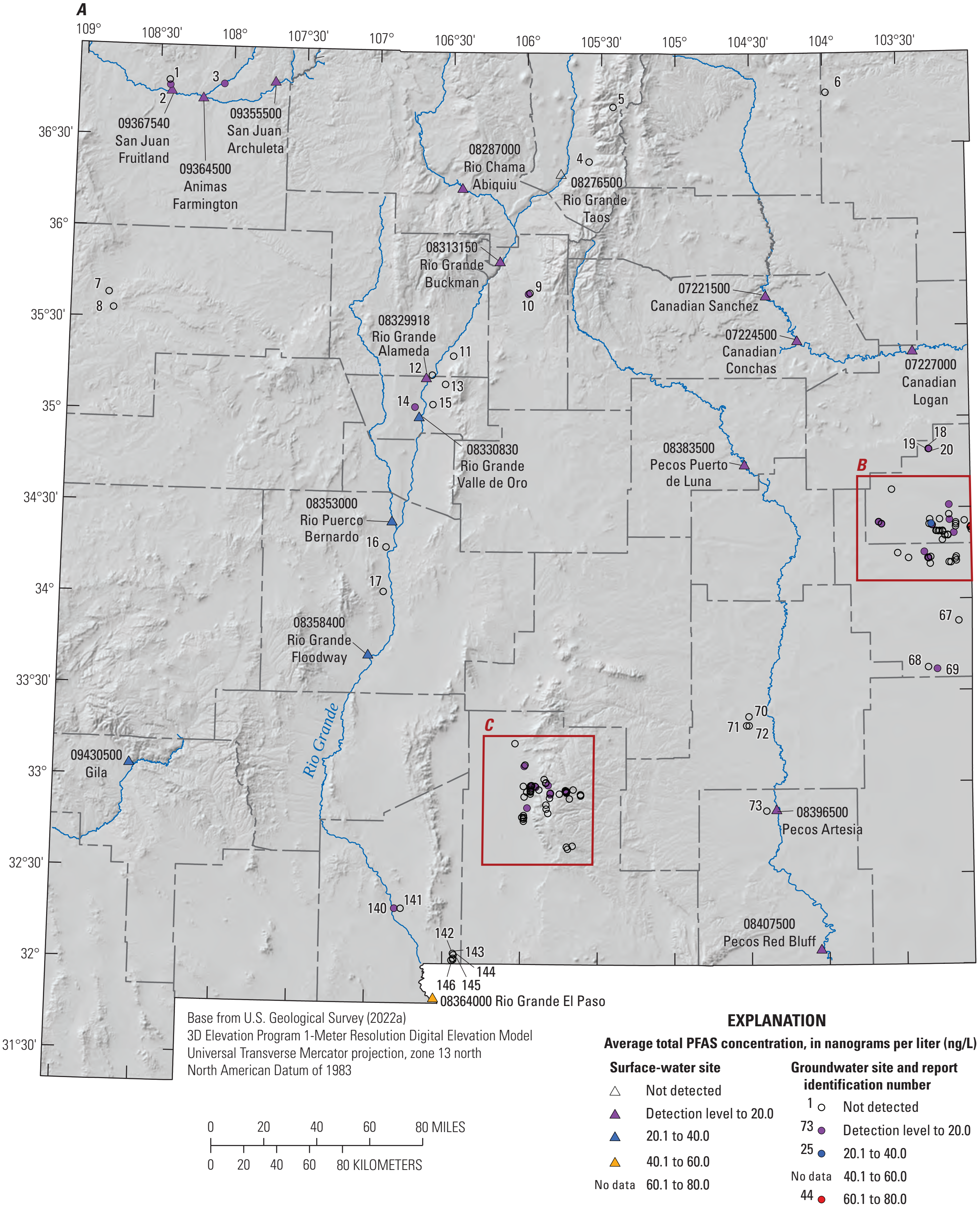
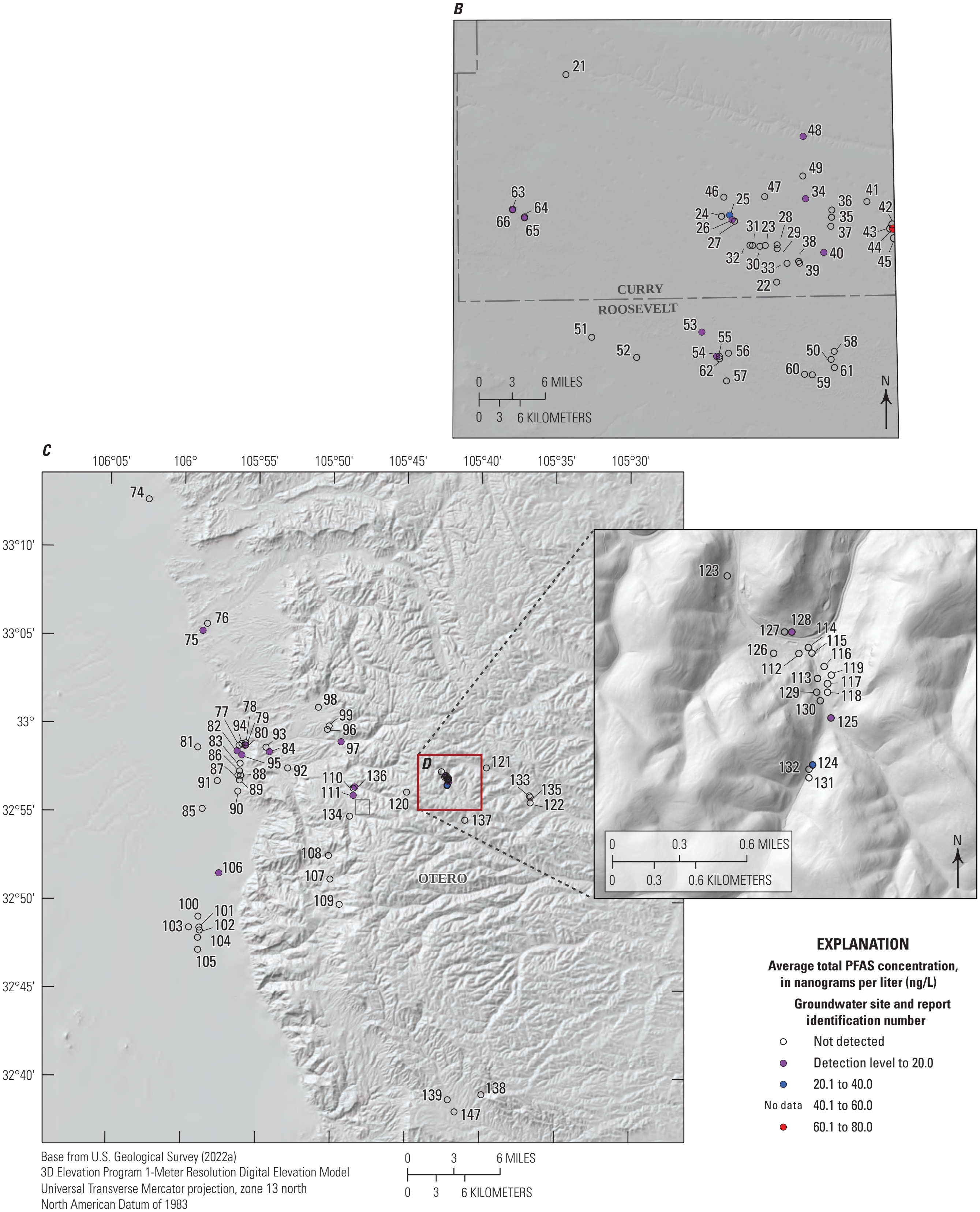


Figure 5. Average total per- and polyfluoroalkyl substance (PFAS) concentrations from groundwater and surface-water sampling locations across New Mexico with *A*, a large-scale map of parts of Curry and Roosevelt Counties, *B*, a large-scale map of part of Otero County, and *C*, a large-scale map of a high-mountain system in Otero County.



Base from U.S. Geological Survey (2022a)
3D Elevation Program 1-Meter Resolution Digital Elevation Model
Universal Transverse Mercator projection, zone 13 north
North American Datum of 1983

Figure 5.—Continued

Table 16. Per- and polyfluoroalkyl substance concentrations from groundwater samples with concentrations above the laboratory detection level, including repeat sampling after detection.

[Values are reported in nanograms per liter. Values in italics represent estimated concentrations greater than the laboratory detection level and less than the laboratory reporting level in effect at the time of sample analysis. --, below the laboratory detection level]

Report identification number	Perfluoroalkylcarboxylic acids							Perfluoroalkyl sulfonic acids				Fluorotelomer sulfonates
	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFBS	PFPeS	PFHxS	PFOS	6:2FTS
2	4.6	--	--	--	--	--	--	--	--	--	--	--
3	--	--	--	--	--	--	--	*1.3*	--	--	--	--
10	--	--	--	--	*1.1*	--	--	--	--	--	*1.1*	--
14	--	--	--	--	--	--	--	--	--	--	*1.3*	--
18.1	--	4.3	2.7	--	--	--	--	--	--	--	--	--
18.2	--	4.4	2.9	--	--	--	--	--	--	--	--	--
18.3	--	4.4	2.6	--	--	--	--	--	--	--	--	--
19.1	--	*2*	*1.3*	--	--	--	--	--	--	--	--	--
19.2	--	*1.1*	--	--	--	--	--	--	--	--	--	--
25.1	7.4	12.9	10.3	--	--	--	--	6.5	*1.5*	2.9	--	--
25.2	5.5	9.4	7	--	--	--	--	4.2	*1.2*	*1.5*	--	--
26.1	--	5	5.4	--	--	--	--	2	--	3.4	--	--
26.2	--	4.5	5.3	--	--	--	--	*1.6*	--	5.1	--	--
34	--	*1.5*	*0.92*	--	--	--	--	*1.2*	--	--	--	--
40	--	2.4	1.6	--	--	--	--	--	--	--	--	--
44.1	17.8	20.1	8	--	--	--	--	28.8	--	--	--	--
44.2	19	19.9	9	--	--	--	--	32.4	--	--	--	--
44.3	15.2	15.1	5.3	--	--	--	--	27.5	--	--	--	--
48.1	--	--	--	--	--	--	--	--	--	--	--	5.8
48.2	--	--	--	--	--	--	--	--	--	--	--	--
53	--	--	--	--	--	--	--	--	--	--	*1.2*	--
54	--	--	--	--	--	--	--	--	--	--	*1.3*	--
63	--	--	--	--	--	--	--	--	--	2	*1.4*	--
64.1	--	--	--	--	--	--	--	*1.5*	*1.2*	11.8	2.9	--
64.2	--	--	--	--	--	--	--	*0.99*	*1.1*	8.4	2.3	--
69	--	*1.1*	--	--	--	--	--	--	--	--	--	--
82	--	--	--	--	--	--	--	--	--	--	--	10.9
84	--	--	--	--	--	--	--	--	--	2.7	--	--
97	--	--	--	--	--	--	--	--	--	2.5	--	--
106	--	--	--	--	8	--	--	--	--	--	--	--
111	--	--	--	--	--	--	--	*0.97*	--	*0.94*	--	--
124	28.7	*1*	4.8	*1.9*	36	0.94	2.8	*1.4*	--	--	--	--
124.1	--	--	--	--	--	--	--	--	--	--	--	--
124.2	--	--	--	--	--	--	--	--	--	--	--	--
125	27	*1.1*	2.4	*1.3*	4.8	--	--	*1.3*	--	--	--	--
125.1	--	--	--	--	--	--	--	--	--	--	--	--
125.2	--	--	--	--	--	--	--	--	--	--	--	--
128	12.7	--	--	--	--	--	--	*1.5*	--	--	--	--
128.1	--	--	--	--	--	--	--	--	--	--	--	--
128.2	--	--	--	--	--	--	--	--	--	--	--	--

Table 16. Per- and polyfluoroalkyl substance concentrations from groundwater samples with concentrations above the laboratory detection level, including repeat sampling after detection.—Continued

[Values are reported in nanograms per liter. Values in italics represent estimated concentrations greater than the laboratory detection level and less than the laboratory reporting level in effect at the time of sample analysis. --, below the laboratory detection level]

Report identification number	Perfluoroalkylcarboxylic acids							Perfluoroalkyl sulfonic acids				Fluorotelomer sulfonates
	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFBS	PFPeS	PFHxS	PFOS	6:2FTS
136	--	--	--	--	--	--	--	*0.91*	--	--	--	--
140	--	--	--	--	--	--	--	--	--	--	1.8	--

perfluorobutanoic acid (PFBA), PFPeA, PFHxA, perfluoropentanesulfonic acid (PFPeS), and PFOS present at one or more of the sites in January and October 2021 (fig. 6*C,D*).

Three springs in a similar geographic area of Otero County—sites 124, 125, and 128 (figs. 1*D* and 5*D*, table 16)—were sampled in April 2021 and had similar concentrations of PFBA and PFBS (fig. 6*E*). Two of the springs also had detections of PFHxA, PFPeA, perfluoroheptanoic acid (PFHpA), and PFOA. In addition, spring 124 had detections of perfluorononanoic acid (PFNA) and PFDA (fig. 6*E*). These three springs were resampled in October 2021 and no PFAS detections were reported by the laboratory for these later samples, despite laboratory detection levels being similar during both time periods. The flow at the sites was greater during the October 2021 sampling, which could reflect contributions of discharge from different groundwater flow paths during this time and (or) dilution of any PFAS that were present at concentrations below laboratory detection levels.

Field Properties

The field properties water temperature, pH, specific conductance, and dissolved oxygen concentration were measured onsite prior to collection of water-quality samples. Groundwater temperature ranged from 5.0 to 32.9 degrees Celsius (°C) and varied on the basis of the location and depth of the groundwater sampled. Field pH values were circumneutral and ranged from 6.7 to 8.8. Specific conductance ranged from 274 to 52,700 microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C). The majority of samples had dissolved-oxygen concentrations greater than 3 milligrams per liter (mg/L), with some sites having concentrations less than 0.5 mg/L, suggesting suboxic or anoxic conditions (sites 7, 8, 12, 15, 16, 140, and 141) (Jurgens and others, 2009).

Water-Quality Standards

Water-chemistry results were compared with EPA maximum contaminant levels (MCL), secondary maximum contaminant levels (SMCL), and health advisories (EPA, 2022a, 2023) (table 17). In 2016, the EPA established a health advisory limit of 70 ng/L for PFOA and PFOS (EPA, 2022a), and after this study was completed, in June 2022, the EPA issued draft health advisory limits for PFOA and PFOS to 0.004 and 0.02 ng/L, respectively. The draft health advisory also set limits of GenX to 10 ng/L and PFBS to 2,000 ng/L (EPA, 2022a). No groundwater sites exceeded the 2016 health advisory limit. The 2022 draft health advisory limits for PFOS and PFOA are below the analytical method detection level (EPA, 2018). A total of seven sites had samples that exceeded an MCL. Two sites (51 and 53) exceeded the MCL for nitrate as nitrogen (10 mg/L), with the maximum concentration being 23.9 mg/L at site 53. The arsenic MCL (10 µg/L) was exceeded at four sites (13, 14, 15, and 17), with the maximum concentration being 41.7 µg/L at site 13. The uranium MCL (30 µg/L) was exceeded at two sites (2 and 53), with the maximum concentration being 214 µg/L at site 2.

Among SMCLs, the total dissolved solids (TDS) SMCL (500 mg/L, defined by the EPA as being for TDS) was exceeded at 59 sites, with the maximum value of dissolved solids (dried at 180 °C) being 58,100 mg/L at site 2. Sulfate had the second most SMCL (250 mg/L) exceedances (41 sites), with a maximum concentration of 33,800 mg/L at site 2. The chloride SMCL of 250 mg/L was exceeded at 24 sites, with a maximum chloride concentration of 5,730 at site 2. No sites exceeded the MCL (4 mg/L) for fluoride; however, 20 sites exceeded the SMCL (2 mg/L), with a maximum fluoride concentration of 2.97 mg/L at site 43. The iron and manganese SMCLs (300 and 50 µg/L, respectively) were exceeded at three and four sites, respectively, with maximum concentrations of iron (1,010 µg/L) and manganese (459 µg/L) at site 12. The SMCL for pH is a range from 6.5 to 8.5, and pH exceeded 8.5 at four sites (7, 8, 14, and 42), with a maximum value of 8.8 at site 7.

Major Ions

Major ions such as calcium, magnesium, sodium, potassium, chloride, sulfate, and bicarbonate dissolve into water as a result of water-rock interactions and also enter into the groundwater through recharge. Major-ion proportions can be represented by a Piper diagram that shows the relative proportions of cations and anions, with sample locations within the plotting regions indicating the dominant ion types (Hem, 1992). Water type can be assessed from the Piper diagram first

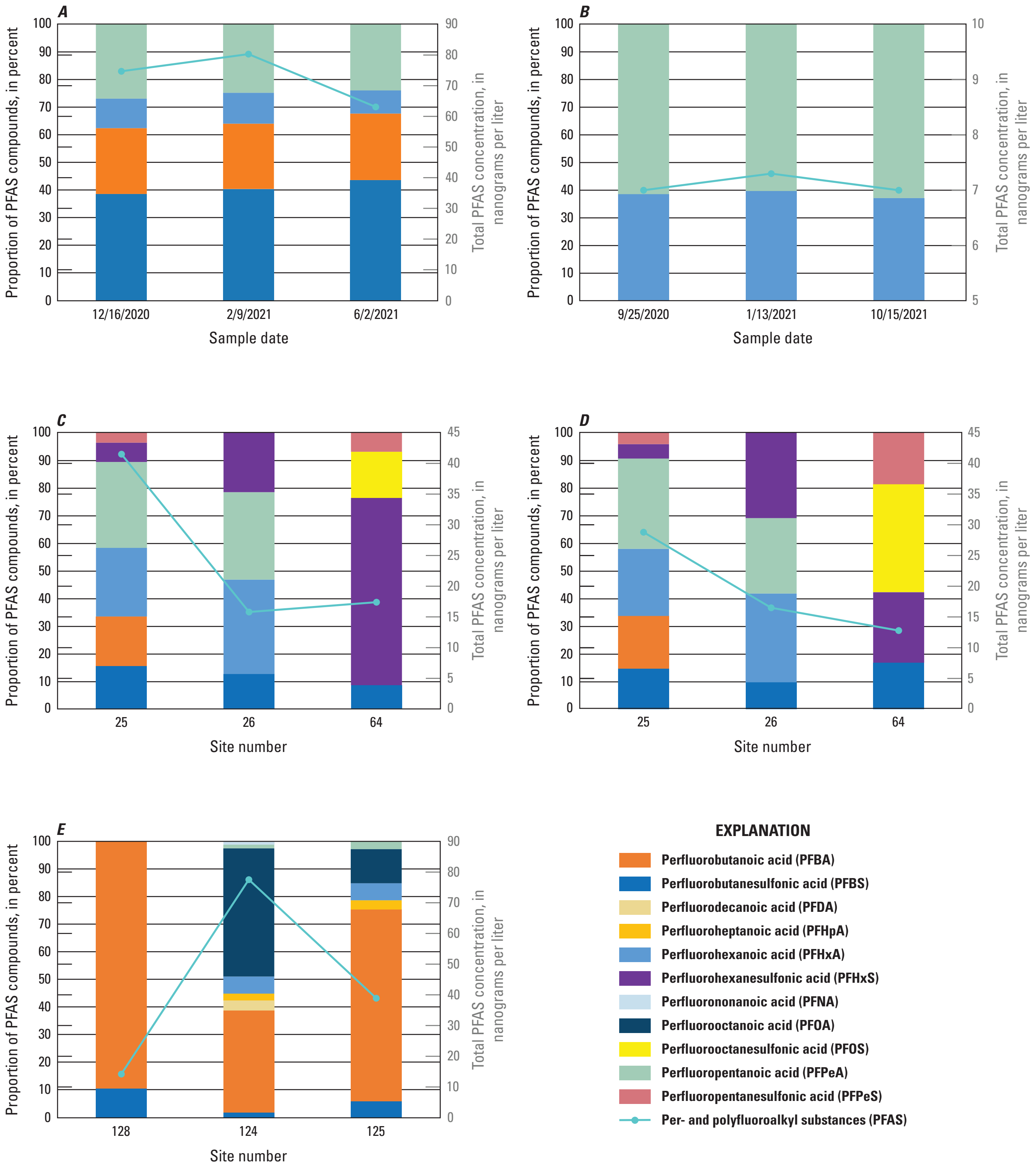


Figure 6. For per- and polyfluoroalkyl substances (PFAS) with detectable concentrations, total concentrations and proportions of total concentrations contributed by individual PFAS for *A*, three groundwater samples collected from site 44 in Curry County between December 2020 and June 2021; *B*, three groundwater samples collected from site 18 in Curry County between September 2020 and October 2021; *C*, groundwater samples collected from sites 25, 26, and 64 in Curry County during January 2021; *D*, groundwater samples collected from sites 25, 26, and 64 in Curry County during October 2021; and *E*, samples collected from springs at sites 124, 125, and 128 in Otero County during April 2021.

Table 17. U.S. Environmental Protection Agency water-quality standards for drinking water (from EPA, 2023).

[MCL, maximum contaminant level; SMCL, secondary maximum contaminant level; µg/L, microgram per liter; NA, not applicable; mg/L, milligram per liter]

Element	Units	Primary drinking-water standard (MCL)	Secondary drinking-water standard (SMCL)
Aluminum (Al)	µg/L	NA	50–200
Antimony (Sb)	µg/L	6	NA
Arsenic (As)	µg/L	10	NA
Chloride (Cl)	mg/L	NA	250
Fluoride (F)	mg/L	4	2
Iron (Fe)	µg/L	NA	300
Manganese (Mn)	µg/L	NA	50
Nitrate (NO_3)	mg/L	10	NA
pH	standard units	NA	6.5–8.5
Sulfate (SO_4)	mg/L	NA	250
Total dissolved solids (TDS)	mg/L	NA	500
Uranium (U)	µg/L	30	NA

by the location of the water sample on the lower triangles, where if a sample plots above 60 percent of a given ion on the triangle sides, then it would be predominantly that ion water type, and if it plots lower than 60 percent for any of the ions it is considered a mixture of water types. The left triangle represents positively charged cations and the right triangle represents negatively charged anions. The large central diamond shows the water samples projected up from their respective locations on the triangles to combine the cation and anion water types. Water type varies throughout the State (fig. 7) and is driven primarily by the rock types and associated minerals present along groundwater flow paths. Therefore, water type tends to be relatively consistent within local geographic areas with the same underlying geology, although water type can evolve along a flow path. Figure 7*A* includes sites located across New Mexico, except in Curry, Roosevelt, or Otero County (fig. 7*B*, *C*); sites in figure 7*A* are discussed next, mostly in order from north to south.

Drinking water in San Juan County is primarily sourced from surface water, so only one public supply well was available to be sampled and two observation wells in the County were also sampled. Sites 1 and 2 are located near a coal deposit and had sodium as the dominant cation; sulfate was the dominant anion for site 2, whereas the anions at site 1 were dominated by a mixture of bicarbonate and sulfate. Site 3 is located near the Animas River and had calcium-bicarbonate-sulfate type water. Groundwater sites 4 and 5 in Taos County had calcium as the dominant cation; site 4 had bicarbonate as the dominant anion, whereas site 5 had a mixture of bicarbonate and sulfate anions. Site 6 in Union County is screened in a young volcanic aquifer and had mixed cation and bicarbonate type water. Two sites in McKinley County (7 and 8) had sodium-bicarbonate-sulfate water, which is likely to represent old water that has undergone cation exchange (Beisner and Jones, 2020).

Groundwater from counties near central New Mexico (Bernalillo, Sandoval, and Santa Fe) generally had calcium and bicarbonate as dominant ions, but with some anomalies. Two sites (9 and 10) in Santa Fe County had calcium-bicarbonate type water. Sites 11 and 12 in Sandoval County had calcium-sodium-bicarbonate type waters. Sites 13, 14, and 15 in Bernalillo County had a mixture of calcium and sodium as the dominant cations and have bicarbonate as the dominant anion, with some chloride influence. Plummer and others (2012) found that groundwater in the Albuquerque area was generally sodium-bicarbonate type west of the Rio Grande and calcium-bicarbonate type east of the Rio Grande, with a narrow north-south trend of mixed-ion water type that may be related to faults parallel to the mountain front in the vicinity of site 13 in this study. South of the aforementioned Counties, two sites (16 and 17) in Socorro County had sodium-chloride type water and may represent interaction with deep basin groundwater or geothermal fluids (Anderholm, 1987). Sites 70–73 in Chaves and Eddy Counties had generally similar calcium-sulfate water types, although site 70 had more influence from sodium and chloride.

In Doña Ana County, site 140 had calcium-mixed anion water type, and site 141 had a higher proportion of sodium. Site 141 had results more similar to other groundwater sampled farther south in Doña Ana County at sites 144, 145, and 146 (with a higher proportion of sodium). Sites 142 and 143 in Doña Ana County had sodium-chloride type waters.

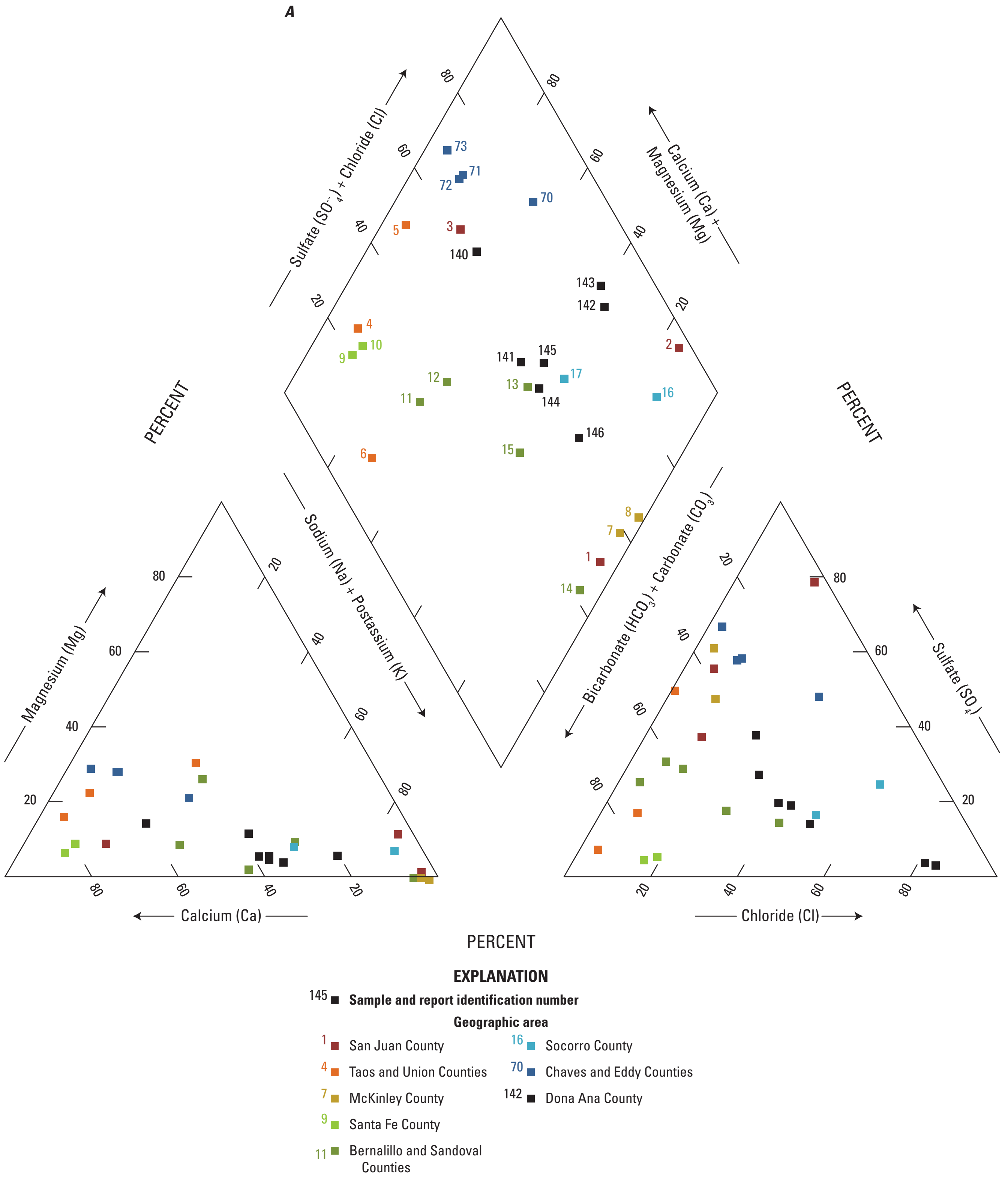
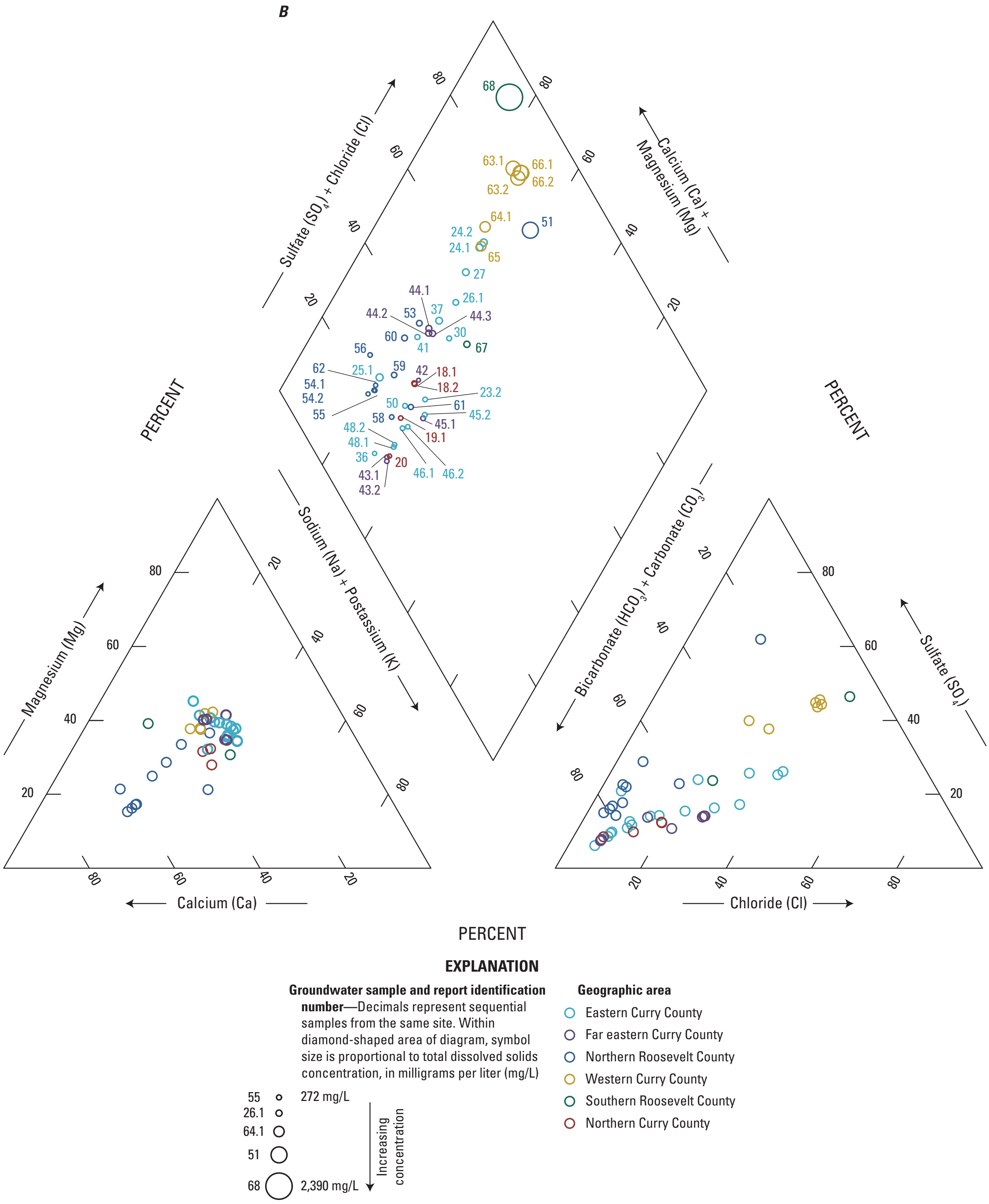


Figure 7. Piper diagrams showing the major-ion proportions of groundwaters and springs collected across *A*, New Mexico, *B*, Curry and Roosevelt Counties, and *C*, Otero County.



EXPLANATION

Groundwater sample and report identification number—Decimals represent sequential samples from the same site. Within diamond-shaped area of diagram, symbol size is proportional to total dissolved solids concentration, in milligrams per liter (mg/L)

55 ○ 272 mg/L
26.1 ○
64.1 ○
51 ○
68 ○ 2,390 mg/L

Increasing concentration

Geographic area

○ Eastern Curry County
○ Far eastern Curry County
○ Northern Roosevelt County
○ Western Curry County
○ Southern Roosevelt County
○ Northern Curry County

Figure 7.—Continued

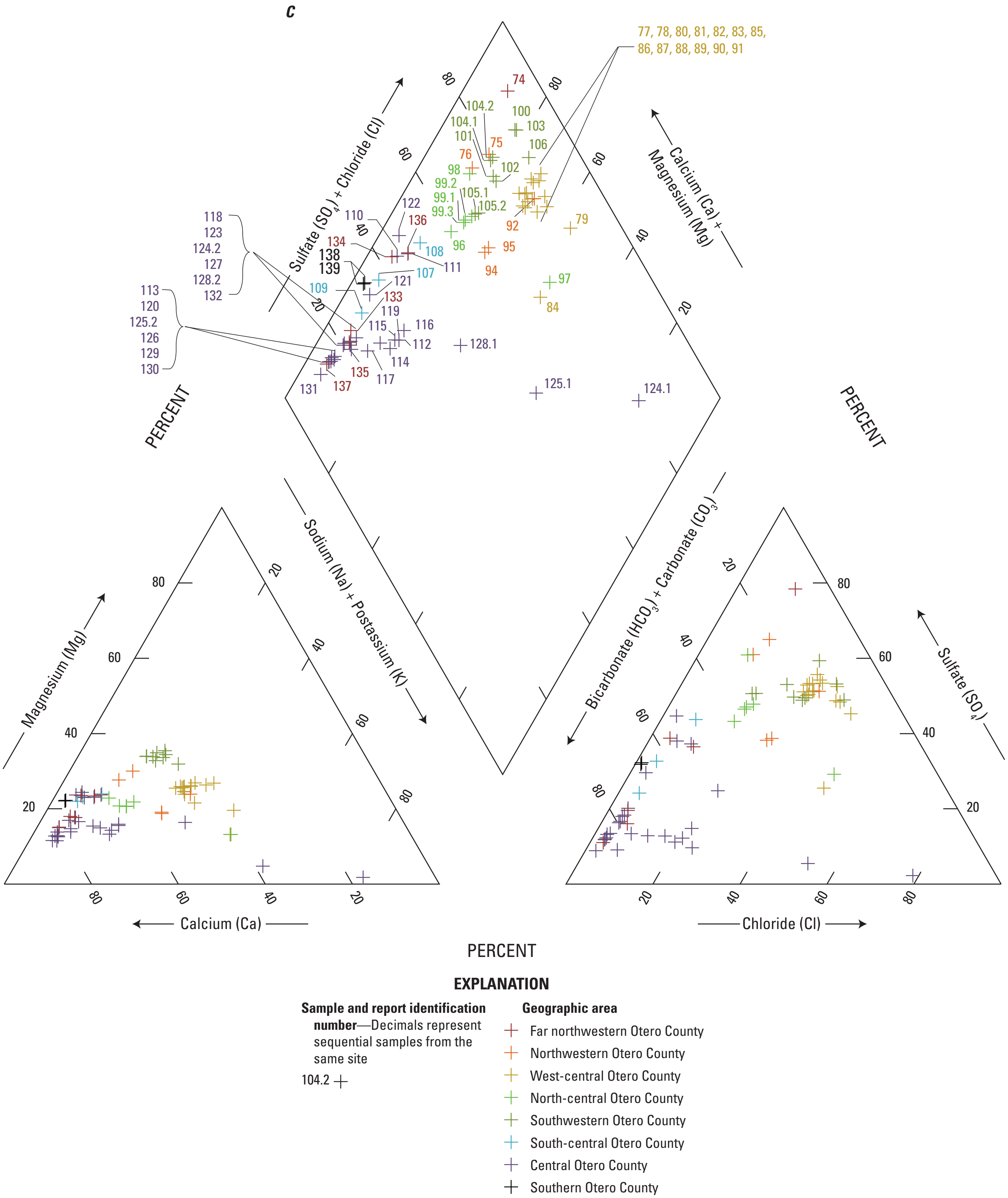


Figure 7.—Continued

Groundwater sampling sites provide dense spatial coverage of parts of Curry and Roosevelt Counties in the High Plains aquifer and of Otero County in south-central New Mexico. Water samples were placed into groups on the basis of their geographic location within each county, which for Curry and Roosevelt Counties were divided up into even north and south, then east and west halves and sometimes given a designation of far (cardinal direction) for areas with high sample density. For Otero County, similar geographic areas were designated with additional subareas including central areas within the cardinal direction designations for areas with high sample density. Water types for samples collected in Curry and Roosevelt Counties ranged from calcium-bicarbonate to mixed cation-mixed anion, with one sample categorized as mixed cation-sulfate type (fig. 7*B*). Analytical results for samples collected in Curry and Roosevelt Counties by Langman and Ellis (2010a, b) suggest groundwater from the Ogallala Formation of the High Plains aquifer typically was a mixed cation-bicarbonate type, with groundwater present in the center of paleochannels having a higher proportion of bicarbonate and upland samples having a higher proportion of sulfate. The Dockum Group underlies the Ogallala Formation and generally had a sodium-chloride type water (Langman and Ellis, 2010a, b); however, groundwater from the Dockum Group was not sampled in this study, and there were no sodium-chloride type waters from samples in Curry and Roosevelt Counties in this study. Groundwater with higher TDS had a higher proportion of sulfate, with site 68 having the highest value (fig. 7*B*). Site 68 is located at the southern end of Roosevelt County and may represent an upland or other distinct water source compared with the other samples collected in Curry and Roosevelt Counties for this study (fig. 1).

Groundwater samples were collected from sites in the Sacramento Mountains on the east side of Otero County, as well as within the basin-fill sediments west of the mountain block (fig. 1). Generally, samples from the mountain-block area were collected from springs or shallow wells completed in bedrock and had a calcium-bicarbonate water type (fig. 8*A*). Samples collected from the mountain block had lower TDS (598 mg/L average) compared with wells screened in the basin-fill sediments west of the mountain block, which had generally higher TDS (1,552 mg/L average) and were more of a mixed cation-sulfate to mixed cation-mixed anion water type. There was one brackish water well in the northern area of Otero County (site 74) that had calcium-sulfate type water. The dominant geologic units of the Sacramento Mountains are the Permian San Andres Limestone (primarily limestone with some dolomite) and the Yeso Formation (sandstone, limestone, dolomite, and gypsum units).

Sites 124, 125, and 128 had samples collected in April 2021 (samples ending with “.1”), and October 2021 (samples ending with “.2”) (table 16). For the April 2021 samples, the water types differed among all three sites, with site 124 having a sodium-chloride type water. On the Piper diagram, the April 2021 sample from site 124 plots farthest from the compositions of groundwater from other sites in that area (112–119, 123, 126, 127, 129–132), with the April sample from site 128 plotting closest to those sample compositions (fig. 8). The October 2021 samples for sites 124, 125, and 128 were more similar to the general group of samples in that area, which have calcium-bicarbonate type waters.

Dissolved Organic Carbon

DOC was detected at low concentrations in 95 percent of the groundwater samples. Three sites had DOC above the highest blank concentration threshold of 3.63 mg/L: site 2 (21.9 mg/L), site 124 (April 2021, 8.83 mg/L), and site 99 (5.06 mg/L).

Nutrients

Nitrate, nitrite, ammonia, and orthophosphate were measured in groundwater samples. Ammonia was only detected at nine sites and ranged from 0.02 to 0.92 mg/L. Orthophosphate as phosphorus was detected in most groundwater sites and ranged from 0.004 to 0.066 mg/L at the 98 sites where it was detected.

Nitrate as nitrogen was less than the laboratory detection level at five sites, with detections ranging in concentration from 0.06 to 23.9 mg/L (site 53). Occurrence of nitrate concentrations greater than 5.0 mg/L as nitrogen may be due to the presence of human-related sources of nitrogen on the land surface, transport to the aquifer by natural and human-related recharge mechanisms, and (or) persistence in the aquifer as a result of favorable geochemical conditions for nitrate (Bexfield and others, 2011). Wells where nitrate as nitrogen was detected above 5 mg/L were located in the High Plains aquifer in Curry and Roosevelt Counties and were screened/completed either no more than 400 ft deep (sites 18, 25, 26, 37, 44, and 53) or were of unknown well depth (sites 27, 51, and 68). Two of these sites (51 and 53) exceeded the MCL of 10 mg/L.

Stable Isotopes

Stable isotopes of oxygen and hydrogen of the water molecule were measured for groundwater samples from this study. The ratio of the two stable isotopes gives an indication of recharge elevation, seasonality, and evaporation (Craig, 1961; Rozanski and others, 1993). The statewide sampling represents water from different regions and aquifers; samples within a region and aquifer can be compared with each other to understand local differences in recharge sources.

Stable isotopic ratios for samples collected across New Mexico ranged from −15.2 to −5.81 for $\delta^{18}O$ and from −121 to −40.6 per mil for δ^2H (fig. 9). Depleted (more negative) values generally represent higher elevation and (or) winter recharge, whereas enriched (less negative) values generally represent lower elevation and (or) summer recharge (Kendall and others, 1995). The most depleted values are located at sites in

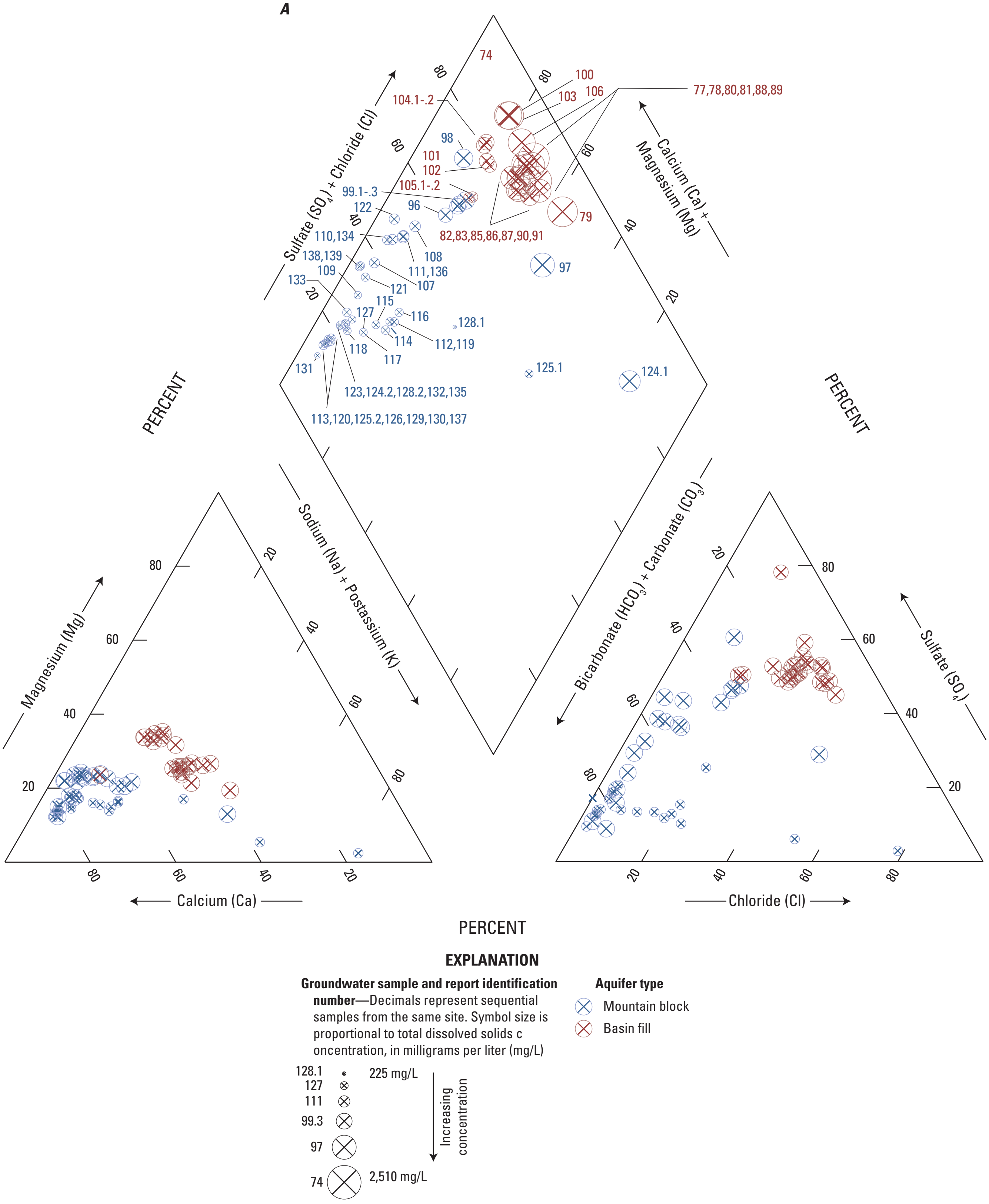
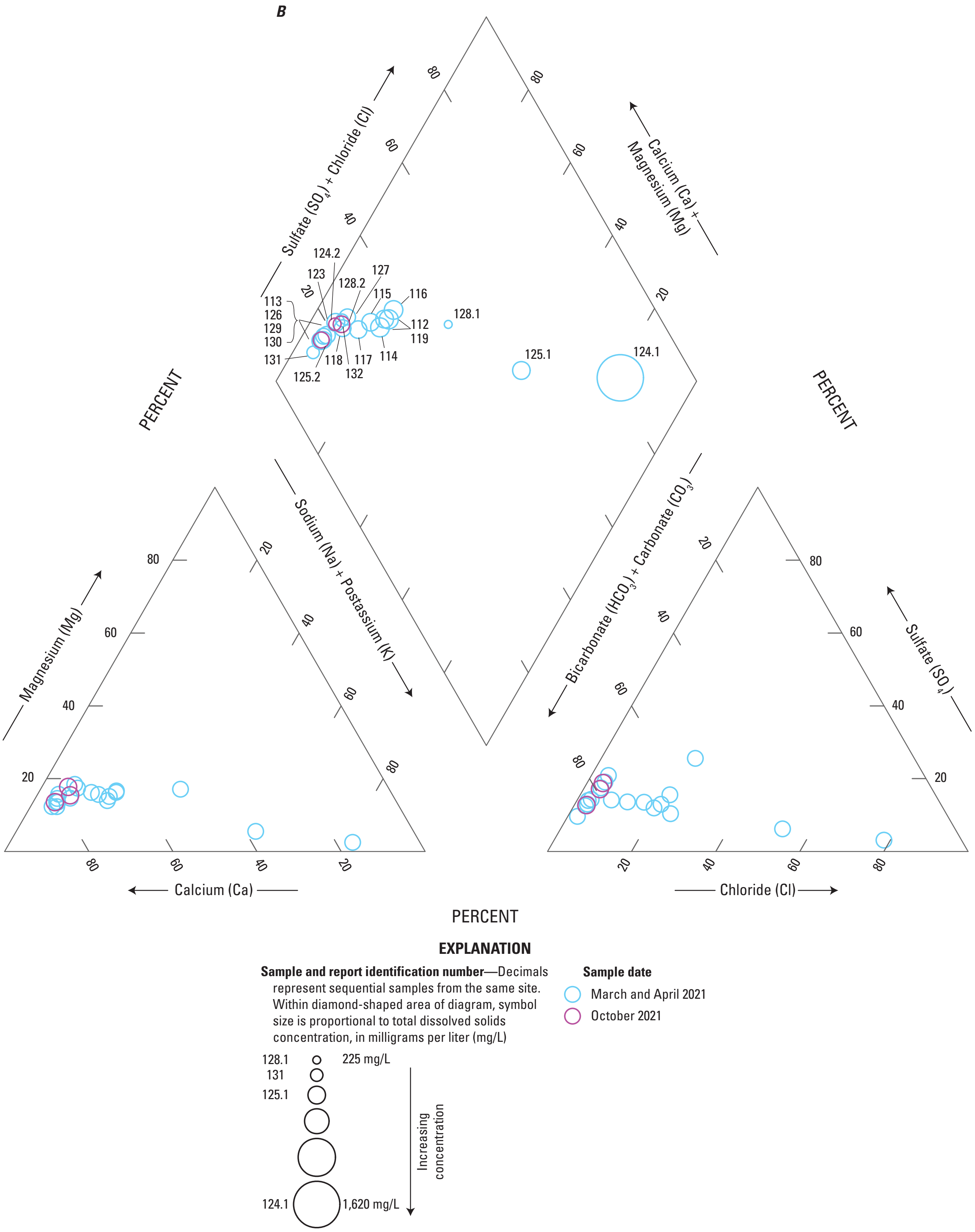


Figure 8. Piper diagrams showing the major-ion proportion of groundwaters and springs collected in Otero County *A*, divided into mountain block and basin-fill aquifers, and *B*, for an area in the mountain block showing temporal variability.



Sample and report identification number—Decimals represent sequential samples from the same site. Within diamond-shaped area of diagram, symbol size is proportional to total dissolved solids concentration, in milligrams per liter (mg/L)

Sample date

○ March and April 2021

○ October 2021

Figure 8.—Continued

the northern part of the State (sites 1–8), as well as at sites near the Rio Grande (sites 11–15) (figs. 1 and 9*A*). The most enriched values, which also indicate an evaporative signature (Kendall and others, 1995), are located in the south-central (sites 70–147) and eastern (sites 18–69) parts of New Mexico (figs. 1 and 9).

Three groundwater samples from Albuquerque, the largest urban area of New Mexico (sites 13–15, fig. 1), have some of the most depleted isotopic values from the study (fig. 9*A*). Plummer and others (2012) conducted a detailed geochemical analysis of water in the Middle Rio Grande Basin in the 1990s, which included site 13 and wells within the same well field as sites 14 and 15. Generally, the most depleted stable isotopic values in Albuquerque were located in the center of the basin, attributed to recharge from the Rio Grande, which is sourced largely from precipitation at higher elevations in the mountains of southern Colorado and northern New Mexico; more enriched isotopic values were located closer to the mountain front. Sites 14 and 15 are located in the central area of the basin, and samples from these sites were more depleted than the sample from site 13, which is located at a higher elevation to the east towards the mountain front. Isotopic signatures at sites 14 and 15 were similar to those of samples collected in 1997 from Plummer and others (2012), being within 0.2 and 0.5 per mil for $\delta^{18}O$ and $\delta^{2}H$, respectively. The site 13 value was more depleted compared to the 1997 value, differing by 0.74 and 5.9 per mil for $\delta^{18}O$ and $\delta^{2}H$, respectively, and suggesting a change in the source of water for that well that may warrant further investigation.

Springs 124, 125, and 128 had PFAS detected in samples collected in April 2021 (table 16), and they plot to the right of the meteoric water line, suggesting an evaporative stable isotopic signature at that time (fig. 10). The springs were resampled in October 2021, when they did not have any PFAS detected and had stable isotopic signatures similar to those of other springs and wells sampled in the area during the April 2021 sampling event (sites 112–128; fig. 10). The samples with PFAS detections may indicate concentration in evaporated water that is localized and not representative of other groundwater in the area. The flow at springs 124, 125, and 128 was higher in October 2021 than in April 2021.

Groundwater Age

Groundwater ages discussed in this section, based on radiocarbon and tritium concentrations, represent an approximation of the length of time since precipitation entered the subsurface and interacted with carbonate minerals in the aquifer matrix.

Radiocarbon (^{14}C) can be used to estimate the length of time since groundwater moved through the subsurface into the saturated part of an aquifer. The carbon species in the water sample are used to interpret the interaction with young carbon from gases in the soil zone, old carbon present as carbonate minerals in the aquifer matrix, and from interaction with organic carbon within the aquifer matrix such as oil and gas deposits. Some of the carbon species interactions occur in an open system condition while the water is moving through the unsaturated zone in contact with soil gas. Once the water enters the saturated zone, then carbon species interact under closed system conditions, and interactions in both open and closed systems influence the carbon species of the water.

The $\delta^{13}C$ ratio varies as the water interacts with carbon sources in the soil zone during recharge and continues to do so as the water interacts with older solid carbonate sources in unconsolidated and bedrock materials (Han and Plummer, 2016). The $\delta^{13}C$ ratio used for the soil and solid carbonate sources can influence the calculation of groundwater age. Solid carbonate $\delta^{13}C$ values generally vary over a few per mil, whereas soil gas $\delta^{13}C$ values vary over a larger range depending on the type of plant respiring CO_2 into the soil zone. Knowledge of the plant community or direct measurement of soil gas $\delta^{13}C$ during groundwater recharge is needed to constrain the groundwater age calculation. Often with older groundwater, soil gas $\delta^{13}C$ is assumed because the groundwater recharged prior to human measurement of soil gas in the recharge area. Table 18 presents a range of possible groundwater ages based on different soil gas values for waters that plot in a region below ^{14}C of 50 pmc and below the zero-age area on figure 11 that indicates radiocarbon decay, where minimum is the younger age and maximum is the older age based on the given soil gas value.

The majority of groundwater samples had ^{14}C values greater than 50 pmc, which precludes the groundwater age from being quantified because of radiocarbon decay (fig. 11; Han and others, 2012). For the samples with ^{14}C values less than 50 pmc that also plot below the zero-age area line, the groundwater has undergone radiocarbon decay and an age can be estimated using the revised Fontes and Garnier solid exchange equations (Han and Plummer, 2013). Soil gas and solid carbonate ^{14}C and $\delta^{13}C$ values are used to calculate the zero-age lines on figure 11. For samples that plot between the zero-age lines, radiocarbon age cannot be quantified and may be explained by geochemical reaction with no radiocarbon decay. Samples that plot above the zero-age area are likely mixtures containing some old and young recharged water. The intersection of Tamers X ($\delta^{13}C$) and Y (^{14}C) represent the starting isotopic composition of the exchange process (Han and Plummer, 2016).

Groundwater age estimates vary on the basis of the $\delta^{13}C$ of the soil gas used in the revised Fontes and Garnier solid exchange equations, and a range of possible soil gas values (–11.5 to –21.4 per mil; Plummer and others, 2012) was used to represent the possible range of groundwater age, which could be refined for areas if soil gas in recharge areas is measured. Some sites only had a quantifiable groundwater age when using −11.5 per mil for the $\delta^{13}C$ of soil gas, including sites 44, 70, 71, 72, 73, 83, 90, 86, 88, and 104, which are located in Curry, Chavez, Eddy, and Otero Counties. Additional investigation of the groundwater flow paths to these wells could help inform what factors influence radiocarbon interaction and establish a reasonable $\delta^{13}C$ soil gas for

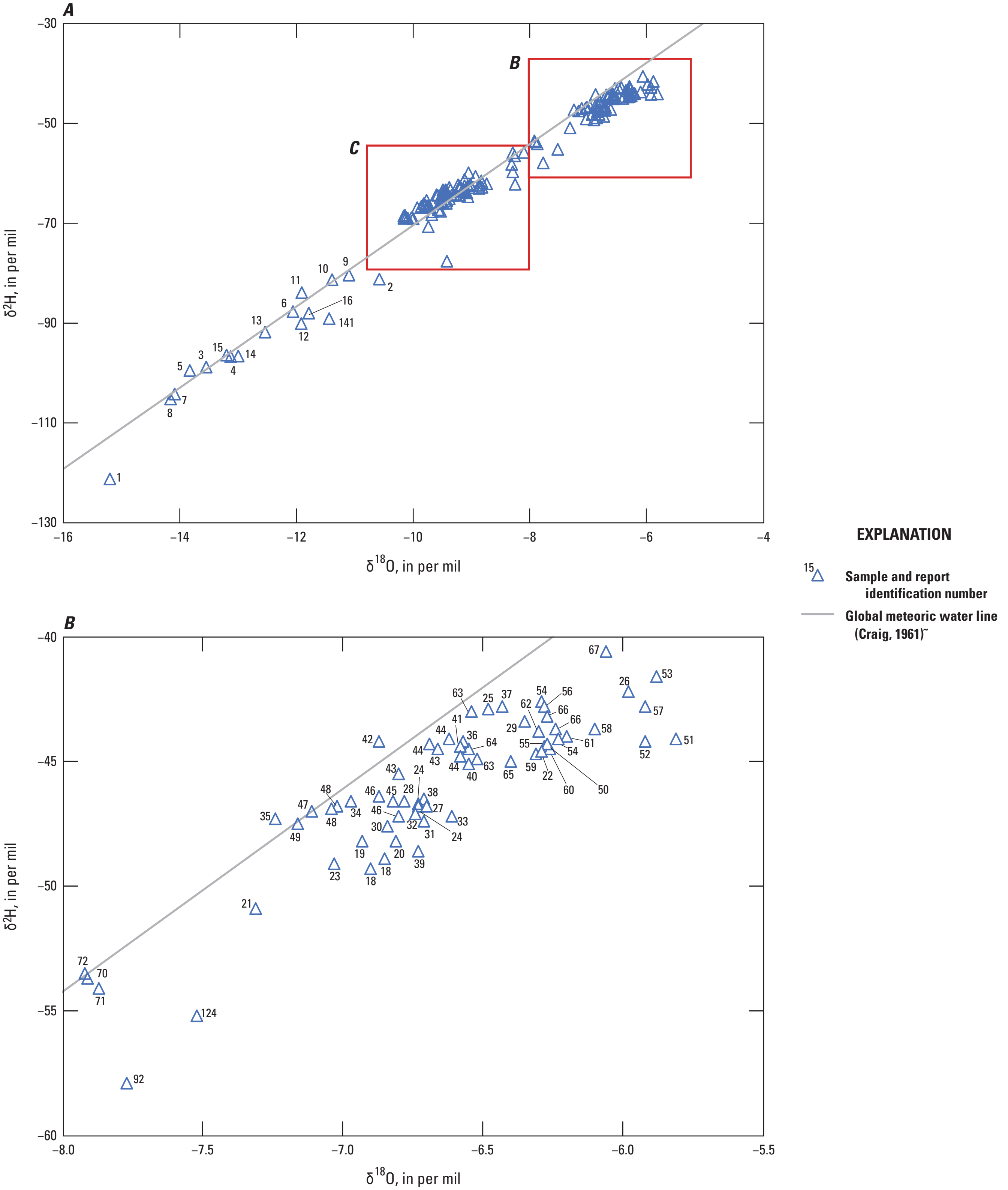


Figure 9. *A*, Stable isotopic ratios of oxygen and hydrogen in groundwaters and springs collected across New Mexico. Inset graphs, *B–C*, represent focused areas of the graph for more detail.

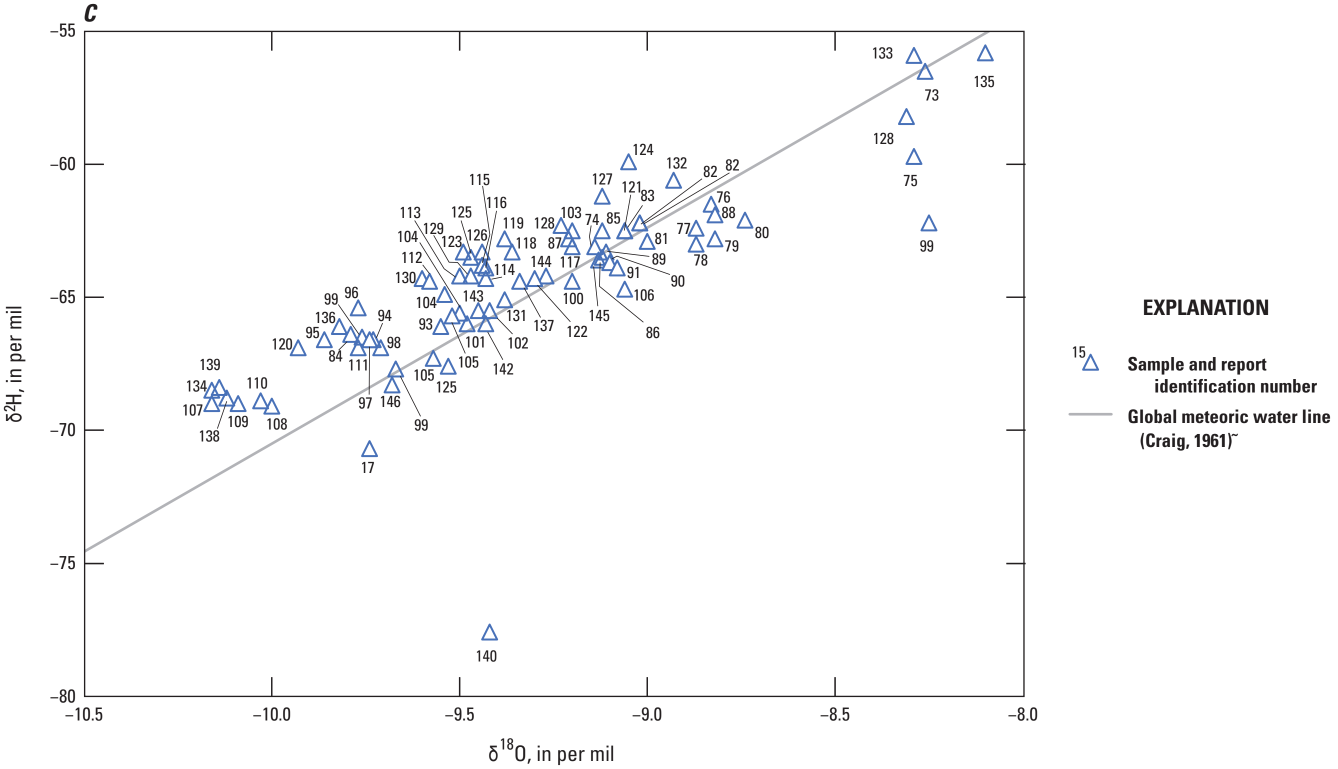


Figure 9.—Continued

the water recharging those aquifer systems. Some of the sites (1, 7, 8, 11, 15, 16, 89, 101, 103, 106, 142, 143, 144, 145, and 146) had groundwater age estimates greater than 10,000 years before present. Site 44 had detections of PFAS and only sample 44.1 had a low groundwater age estimate (64 years before present) when using −11.5 per mil for soil gas. Site 106 is located on a golf course and had a detection of PFOA, while also having low tritium below the laboratory reporting level and an old groundwater age (table 18). Irrigation using groundwater with an old radiocarbon age that reinfiltrated into the subsurface is a possible explanation for the presence of PFOA in old water at the site. The other groundwater sites from this study with quantifiable radiocarbon groundwater age had PFAS below the laboratory detection level.

Two groundwater samples from the Colorado Plateaus aquifers in McKinley County (sites 7 and 8) had the most depleted $\delta^{13}C$ values from the dataset (−12.67 and −13.38 per mil, respectively) and low ^{14}C (0.96 and 2.66 pmc, respectively) (fig. 11). The estimated groundwater ages for these samples ranged from 25,728 to 39,406 years before present (table 18). Other groundwater studies in the area have similarly low $\delta^{13}C$, suggesting interaction with fossil organic matter (Han and others, 2012), potentially related to naturally occurring hydrocarbon deposits (Dam, 1995).

Tritium is a useful indicator of water recharged following the aboveground nuclear testing of the 1950s (Lindsey and others, 2019). Semiannual (February and August) tritium concentrations from 1953 to 2012 for quadrangles covering the majority of New Mexico (latitude 31 through 35 degrees north and longitude −100 through −110 degrees west) from Michel and others (2018) and Jurgens (2018) are shown on figure 12. The premodern threshold for New Mexico is 0.35 pCi/L, which was determined as part of this study by assuming that the average of the 2008–12 precipitation data represents a background value for the area and then decaying that concentration from 1952 to the sample year for this study, which was primarily 2021, with a few samples collected in late 2020. The modern threshold was determined by finding the minimum post bomb-pulse tritium value decayed to 2021 for the aforementioned tritium data from precipitation. Modern thresholds determined for the two latitude-longitude quadrangles containing the most samples from the study were slightly different at 3.19 for latitude 33 to 35, longitude −100 to −105 (which includes sites 18–69, 74−76, and 98) and 3.30 pCi/L

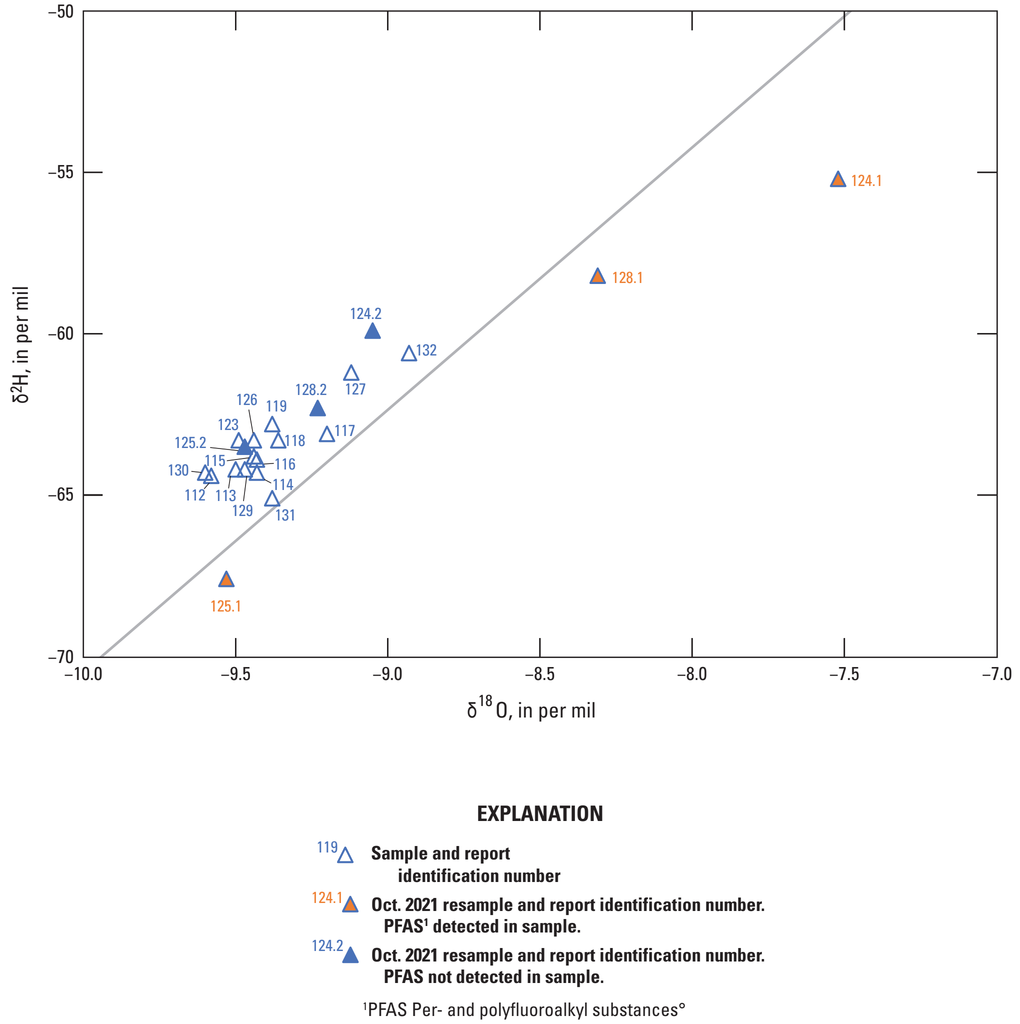


Figure 10. Stable isotopic ratios of oxygen and hydrogen for groundwater and spring samples from a focused area in Otero County. The solid line represents the global meteoric water line (Craig, 1961).

for latitude 31 to 33, longitude −105 to −110 (which includes sites 77−97, and 99−146) (fig. 12). Other quadrangles contained less samples and had similar modern thresholds including: 2.11 pCi/L for latitude 31 to 33, longitude −100 to −105 (including sites 70−73), 3.78 pCi/L for latitude 33 to 35, longitude −105 to −110 (including sites 16 and 17), 3.70 pCi/L for latitude 35 to 37, longitude −100 to −105 (including site 6), and 4.58 pCi/L for latitude 35 to 37, longitude −105 to −110 (including sites 1–5 and 7–15).

Tritium from this study ranged from less than the laboratory sample specific critical level to 17.56 pCi/L. The majority of the samples were above the laboratory sample specific critical level and ranged from 0.2 to 17.56 pCi/L. There were 41 samples in the premodern category (including one sample from site 11 that had an elevated censoring level of 0.58 pCi/L), 40 samples in the mixed category, and 48 samples in the modern category (table 18 and appendix 1).

Surface-Water Diversions

Surface-water diversions within public water systems were also sampled to provide a comprehensive assessment of PFAS in sources of water to those public water systems (table 1). The PFAS detections are reported in table 19. Only three of six of the diversion sites had PFAS detected, and the detections of PFHxS and PFOS were all below the reporting level.

Surface Water

This discussion of surface-water chemistry addresses PFAS results first, followed by results for general chemistry, wastewater chemistry, DOC, and major and trace elements.

Table 18. Results of tritium and carbon isotope analyses.

[Data are available from the National Water Information System (U.S. Geological Survey [USGS], 2022b). Dates are shown as month, day, year. ^{14}C, carbon-14; δ^{13}C, normalized ratio of carbon-13 and carbon-12; pmc, percent modern carbon; pM, absolute modern carbon; per mil, per thousand; BP, before present; pCi/L, picocurie per liter; R, result is below the sample-specific critical level; NA, not available; *, radiocarbon sample broken by the lab]

Report identification number	Sample date	Denormalized ^{14}C (pmc)	Normalized ^{14}C (pM)	δ^{13}C (per mil)	Minimum corrected age (δ^{13}C soil gas −21.4 per mil) (years BP)	Maximum corrected age (δ^{13}C soil gas −11.5 per mil) (years BP)	Tritium concentration (pCi/L)	Tritium age category (Lindsey and others, 2019)
1	12/02/20	0.76	0.74	−7.36	30,883	35,894	0.04 R	Premodern
2	11/19/20	87.50	85.49	−9.40	NA	NA	6.11	Modern
3	10/28/20	84.24	83.11	−14.23	NA	NA	16.72	Modern
4	08/10/21	97.94	96.42	−13.14	NA	NA	11.28	Modern
5	08/10/21	80.90	79.11	−9.77	NA	NA	16.82	Modern
6	08/11/20	72.36	70.39	−7.27	NA	NA	0.0 R	Premodern
7	04/26/21	0.98	0.96	−12.67	33,694	39,406	0.01 R	Premodern
8	04/26/21	2.70	2.66	−13.38	25,728	31,259	0.00 R	Premodern
9	09/15/20	80.44	78.99	−11.92	NA	NA	4.09	Mixed
10	09/15/20	71.27	69.95	−11.67	NA	NA	2.33	Mixed
11	09/11/20	10.20	9.92	−7.34	9,247	14,503	0.58 R	Premodern
12	09/29/20	98.10	96.36	−12.08	NA	NA	10.01	Modern
13*	02/09/21	NA	NA	NA	NA	NA	0.00 R	Premodern
14*	02/09/21	NA	NA	NA	NA	NA	0.63 R	Premodern
15	09/25/20	16.52	16.12	−8.64	6,926	11,736	0.19 R	Premodern
16	09/28/20	1.01	0.98	−4.67	23,428	29,050	0.15 R	Premodern
17	09/28/20	42.37	41.33	−8.59	NA	4,162	0.15 R	Premodern
18.1	09/25/20	67.84	65.70	−5.03	NA	NA	0.22	Premodern
18.2	01/13/21	67.73	65.61	−5.10	NA	NA	0.38	Mixed
19.1	01/13/21	68.20	66.04	−4.91	NA	NA	0.02 R	Premodern
20	01/13/21	68.56	66.46	−5.47	NA	NA	0.20	Premodern
24.2	05/12/21	66.42	64.24	−4.31	NA	NA	2.05	Mixed
25.1	01/12/21	95.90	94.10	−11.49	NA	NA	7.88	Modern
26.1	01/12/21	61.93	59.90	−4.31	NA	NA	3.50	Modern
27	05/18/21	67.46	65.34	−5.01	NA	NA	2.15	Mixed
30	05/18/21	62.22	60.22	−4.66	NA	NA	0.29	Premodern
37	12/16/20	68.89	66.91	−6.46	NA	NA	3.35	Modern
41	11/17/20	60.59	58.67	−4.97	NA	NA	1.05	Mixed

Table 18. Results of tritium and carbon isotope analyses.—Continued

[Data are available from the National Water Information System (U.S. Geological Survey [USGS], 2022b). Dates are shown as month, day, year. ^{14}C, carbon-14; δ^{13}C, normalized ratio of carbon-13 and carbon-12; pmc, percent modern carbon; pM, absolute modern carbon; per mil, per thousand; BP, before present; pCi/L, picocurie per liter; R, result is below the sample-specific critical level; NA, not available; *, radiocarbon sample broken by the lab]

Report identification number	Sample date	Denormalized ^{14}C (pmc)	Normalized ^{14}C (pM)	δ^{13}C (per mil)	Minimum corrected age (δ^{13}C soil gas –21.4 per mil) (years BP)	Maximum corrected age (δ^{13}C soil gas –11.5 per mil) (years BP)	Tritium concentration (pCi/L)	Tritium age category (Lindsey and others, 2019)
43	12/16/20	55.04	53.33	−5.25	NA	NA	0.2 R	Premodern
44.1	12/16/20	50.98	49.51	−6.48	NA	64	2.38	Mixed
45.1*	02/09/21	NA	NA	NA	NA	NA	0.14 R	Premodern
45.2	06/02/21	51.84	50.41	−4.38	NA	NA	NA	NA
46.2	05/12/21	66.38	64.18	−4.16	NA	NA	0.11 R	Premodern
48.1	09/09/20	54.06	52.38	−5.25	NA	NA	0.02 R	Premodern
50	11/18/20	73.58	71.30	−5.31	NA	NA	0.00 R	Premodern
51	05/18/21	78.85	76.52	−5.98	NA	NA	4.8	Modern
53	08/25/20	87.59	84.82	−4.99	NA	NA	3.53	Modern
54.1	08/26/20	84.36	82.03	−7.03	NA	NA	1.06	Mixed
55	11/17/20	82.15	79.94	−7.42	NA	NA	0.18 R	Premodern
56	12/15/20	80.15	78.07	−7.89	NA	NA	0.73	Mixed
58	08/26/20	79.45	77.07	−5.85	NA	NA	0.08 R	Premodern
59	05/11/21	77.18	74.86	−5.72	NA	NA	0.4	Mixed
60	11/18/20	77.30	74.93	−5.48	NA	NA	0.14 R	Premodern
61	05/11/21	74.21	71.85	−4.84	NA	NA	0.16 R	Premodern
62	05/11/21	84.01	81.67	−6.86	NA	NA	0.91	Mixed
63.1	08/25/20	96.52	93.16	−3.37	NA	NA	2.71	Mixed
64.1	01/14/21	84.97	82.36	−5.42	NA	NA	3.68	Modern
65	01/14/21	81.67	78.96	−4.13	NA	NA	1.42	Mixed
66.1	12/15/20	96.32	93.11	−4.12	NA	NA	4.33	Modern
67	09/08/20	50.70	49.10	−5.02	NA	NA	0.88	Mixed
68	06/09/21	91.82	89.16	−6.30	NA	NA	1.03	Mixed
70	10/28/20	47.20	45.97	−7.89	NA	2,425	1.57	Mixed
71	10/28/20	49.03	47.76	−7.97	NA	2,216	1.14	Mixed
72	10/28/20	47.19	45.97	−7.97	NA	2,550	0.92	Mixed
73	08/18/21	34.6	33.64	−6.88	NA	3,711	0.58	Mixed
74*	02/09/21	NA	NA	NA	NA	NA	0.05 R	Premodern

Table 18. Results of tritium and carbon isotope analyses.—Continued

[Data are available from the National Water Information System (U.S. Geological Survey [USGS], 2022b). Dates are shown as month, day, year. ^{14}C, carbon-14; $\delta^{13}C$, normalized ratio of carbon-13 and carbon-12; pmc, percent modern carbon; pM, absolute modern carbon; per mil, per thousand; BP, before present; pCi/L, picocurie per liter; R, result is below the sample-specific critical level; NA, not available; *, radiocarbon sample broken by the lab]

Report identification number	Sample date	Denormalized ^{14}C (pmc)	Normalized ^{14}C (pM)	$\delta^{13}C$ (per mil)	Minimum corrected age ($\delta^{13}C$ soil gas −21.4 per mil) (years BP)	Maximum corrected age ($\delta^{13}C$ soil gas −11.5 per mil) (years BP)	Tritium concentration (pCi/L)	Tritium age category (Lindsey and others, 2019)
75	01/26/21	80.75	78.41	−6.32	NA	NA	1.83	Mixed
76	01/26/21	78.28	76.05	−6.54	NA	NA	1.70	Mixed
77	12/30/20	89.80	87.71	−9.27	NA	NA	3.56	Modern
78	12/30/20	87.41	85.47	−9.79	NA	NA	3.23	Mixed
79	12/30/20	57.66	56.15	−7.81	NA	NA	2.49	Mixed
80	12/29/20	83.11	81.23	−9.61	NA	NA	2.71	Mixed
81	01/27/21	73.94	72.11	−8.44	NA	NA	0.70	Mixed
82.1	09/17/20	66.62	64.95	−8.37	NA	NA	1.58	Mixed
83	01/27/21	26.80	26.00	−5.86	NA	4,328	0.93	Mixed
84	04/30/21	64.73	63.22	−9.15	NA	NA	3.20	Modern
85*	02/11/21	NA	NA	NA	NA	NA	0.89	Mixed
86	01/27/21	45.19	43.95	−7.13	NA	1,826	2.71	Mixed
87*	02/09/21	NA	NA	NA	NA	NA	0.25	Premodern
88	01/27/21	49.45	48.11	−7.29	NA	1,268	0.68	Mixed
89	01/27/21	3.65	3.53	−3.96	10,699	16,280	0.35	Mixed
90	05/25/21	33.73	32.76	−6.36	NA	3,270	0.22	Premodern
91	05/27/21	78.5	76.7	−9.36	NA	NA	0.89	Mixed
94	12/30/20	74.89	73.05	−8.64	NA	NA	3.45	Modern
96	04/29/21	67.83	66.26	−9.26	NA	NA	2.86	Mixed
97	04/30/21	63.57	62.11	−9.34	NA	NA	3.11	Mixed
98	04/30/21	54.01	52.62	−7.97	NA	NA	1.21	Mixed
99.1	04/29/21	73.86	72.31	−10.37	NA	NA	2.76	Mixed
99.2	04/29/21	83.15	81.38	−10.19	NA	NA	7.02	Modern
99.3	04/29/21	73.73	72.20	−10.49	NA	NA	2.53	Mixed
100	11/05/20	19.42	18.88	−6.95	3,316	8,555	0.21	Premodern
101	12/22/20	10.92	10.58	−5.28	5,543	10,793	0.18 R	Premodern
102	08/17/21	22.28	21.63	−6.09	676	6,137	0.04 R	Premodern
103	11/05/20	16.08	15.63	−6.86	4,852	10,035	0.10 R	Premodern

Table 18. Results of tritium and carbon isotope analyses.—Continued

[Data are available from the National Water Information System (U.S. Geological Survey [USGS], 2022b). Dates are shown as month, day, year. ^{14}C, carbon-14; $\delta^{13}C$, normalized ratio of carbon-13 and carbon-12; pmc, percent modern carbon; pM, absolute modern carbon; per mil, per thousand; BP, before present; pCi/L, picocurie per liter; R, result is below the sample-specific critical level; NA, not available; *, radiocarbon sample broken by the lab]

Report identification number	Sample date	Denormalized ^{14}C (pmc)	Normalized ^{14}C (pM)	$\delta^{13}C$ (per mil)	Minimum corrected age ($\delta^{13}C$ soil gas −21.4 per mil) (years BP)	Maximum corrected age ($\delta^{13}C$ soil gas −11.5 per mil) (years BP)	Tritium concentration (pCi/L)	Tritium age category (Lindsey and others, 2019)
104.1	09/17/20	27.24	26.44	−6.15	NA	4,673	0.33 R	Premodern
104.2	04/15/21	27.63	26.82	−6.20	NA	4,605	0.07 R	Premodern
105.1	09/18/20	15.39	14.90	−4.91	2,040	7,266	0.26 R	Premodern
105.2	04/15/21	15.60	15.11	−4.97	2,011	7,256	0.04 R	Premodern
106	08/16/21	12.71	12.35	−6.61	6,246	11,605	0.16 R	Premodern
107	05/26/21	76.28	74.74	−10.74	NA	NA	4.12	Modern
108	05/25/21	69.3	67.71	−9.34	NA	NA	2.88	Mixed
109	05/25/21	80.38	78.59	−9.73	NA	NA	4.02	Modern
110	12/29/20	65.44	63.92	−9.32	NA	NA	3.40	Modern
111	12/29/20	85.45	83.99	−12.37	NA	NA	3.82	Modern
112	03/30/21	83.64	82.04	−11.33	NA	NA	6.66	Modern
113	04/14/21	90.75	89.02	−11.32	NA	NA	7.22	Modern
114	03/30/21	87.64	85.96	−11.30	NA	NA	7.39	Modern
115	03/30/21	89.84	88.27	−12.15	NA	NA	6.53	Modern
116	03/30/21	85.47	83.81	−11.15	NA	NA	6.41	Modern
117	03/31/21	87.31	85.56	−10.82	NA	NA	6.35	Modern
118	03/31/21	82.26	80.56	−10.50	NA	NA	4.20	Modern
119	04/01/21	88.44	86.76	−11.36	NA	NA	6.14	Modern
120	04/28/21	82.68	81.01	−10.79	NA	NA	6.87	Modern
121	01/27/21	65.32	63.80	−9.18	NA	NA	2.95	Mixed
122	01/26/21	58.23	56.84	−8.90	NA	NA	3.18	Mixed
123	04/14/21	87.89	86.03	−10.28	NA	NA	6.08	Modern
124.1	04/13/21	103.66	100.88	−7.39	NA	NA	14.59	Modern
125.1	04/14/21	101.63	99.13	−8.54	NA	NA	17.56	Modern
126	04/16/21	86.26	84.39	−10.00	NA	NA	5.56	Modern
127	04/14/21	97.12	95.07	−10.32	NA	NA	7.26	Modern
128.1	04/14/21	101.34	98.47	−6.65	NA	NA	11.94	Modern
129	03/31/21	86.55	84.73	−10.36	NA	NA	6.53	Modern

Table 18. Results of tritium and carbon isotope analyses.—Continued

[Data are available from the National Water Information System (U.S. Geological Survey [USGS], 2022b). Dates are shown as month, day, year. ^{14}C, carbon-14; $\delta^{13}C$, normalized ratio of carbon-13 and carbon-12; pmc, percent modern carbon; pM, absolute modern carbon; per mil, per thousand; BP, before present; pCi/L, picocurie per liter; R, result is below the sample-specific critical level; NA, not available; *, radiocarbon sample broken by the lab]

Report identification number	Sample date	Denormalized ^{14}C (pmc)	Normalized ^{14}C (pM)	$\delta^{13}C$ (per mil)	Minimum corrected age ($\delta^{13}C$ soil gas −21.4 per mil) (years BP)	Maximum corrected age ($\delta^{13}C$ soil gas −11.5 per mil) (years BP)	Tritium concentration (pCi/L)	Tritium age category (Lindsey and others, 2019)
130	04/01/21	85.82	84.01	−10.32	NA	NA	6.50	Modern
131	04/13/21	103.17	101.22	−11.41	NA	NA	9.34	Modern
132	04/13/21	103.58	101.44	−10.55	NA	NA	8.70	Modern
133	01/27/21	90.94	89.11	−10.81	NA	NA	5.33	Modern
134	01/28/21	65.71	64.18	−9.20	NA	NA	3.61	Modern
135	01/27/21	94.56	92.61	−10.55	NA	NA	5.39	Modern
136	01/28/21	81.71	80.16	−11.40	NA	NA	3.48	Modern
137	04/16/21	79.50	77.76	−9.93	NA	NA	5.20	Modern
138	04/28/21	70.76	69.11	−9.20	NA	NA	5.60	Modern
139	04/27/21	71.14	69.48	−9.19	NA	NA	4.86	Modern
140	09/29/20	96.86	94.74	−9.95	NA	NA	11.47	Modern
141	09/29/20	57.47	56.10	−8.99	NA	NA	0.06 R	Premodern
142	01/14/21	7.19	7.02	−9.21	14,173	19,690	0.00 R	Premodern
143	01/13/21	7.45	7.27	−9.08	13,748	19,249	0.26	Premodern
144	01/14/21	20.72	20.23	−9.07	5,289	10,720	0.14 R	Premodern
145	01/13/21	10.86	10.60	−8.71	10,253	15,700	0.12 R	Premodern
146	01/13/21	12.24	11.93	−8.16	8,578	14,138	0.21 R	Premodern
147	04/27/21	78.01	74.81	−10.17	NA	NA	4.68	Modern

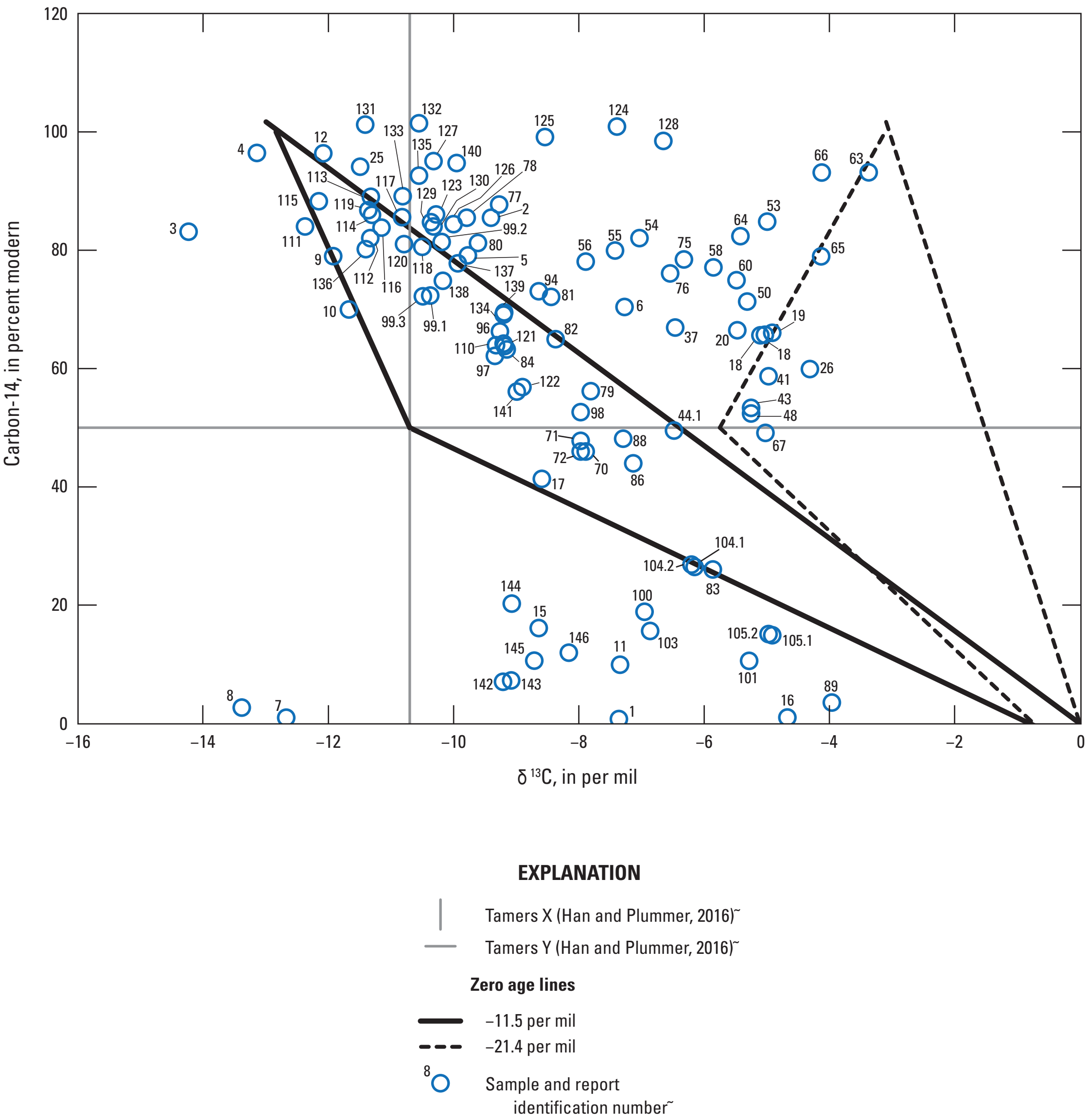


Figure 11. Carbon isotopic values for groundwater and spring samples collected throughout New Mexico.

Per- and Polyfluoroalkyl Substances

Several large rivers of New Mexico were sampled at multiple locations. Of the 18 surface-water locations, only 1 did not have any PFAS detected (Rio Grande Taos, sampled only twice). In sites that were sampled more than five times (table 2), Pecos Puerto de Luna had the fewest detections, with only one of seven sampling events having detections above the detection level. Rio Grande Valle de Oro and Rio Grande El Paso had detections at every sampling event. PFPeA was the most frequently detected PFAS across all sites and events (57 instances, ranging from 1.0 to 29 ng/L), and PFBS was the second most frequently detected PFAS (53 instances, ranging from 1.0 to 93 ng/L). Total PFAS concentrations ranged from 1.0 to 155.4 ng/L at Rio Grande Valle de Oro, which had the greatest single concentration of a PFAS, with 93 ng/L of PFBS.

The Rio Grande was sampled at five locations spanning the State of New Mexico from north to south (fig. 5) and results are discussed here from upstream to downstream order. The most upstream site, Rio Grande Taos, had no PFAS detected in either of its two sampling events. The next downstream site was Rio Grande Buckman, which had low-level detections of one or more of the following: PFPeA, PFBS, and 6:2 fluorotelomer sulfonate (6:2FTS) for samples collected between August 2020 and February 2021, with total PFAS concentrations ranging from 1 to 4.7 ng/L; three samples (collected in March, August, and September 2021) had no PFAS detected (fig. 13*A*). Rio Grande Alameda had no detections in one sample and low-level detections of PFBA, PFPeA, PFHxA, PFOA, and PFBS in nine other samples, with one to five compounds detected in any of those nine individual samples and total PFAS ranging from 1.1 to 8.2 ng/L (fig. 13*B*). The next downstream site was Rio Grande Valle de Oro,

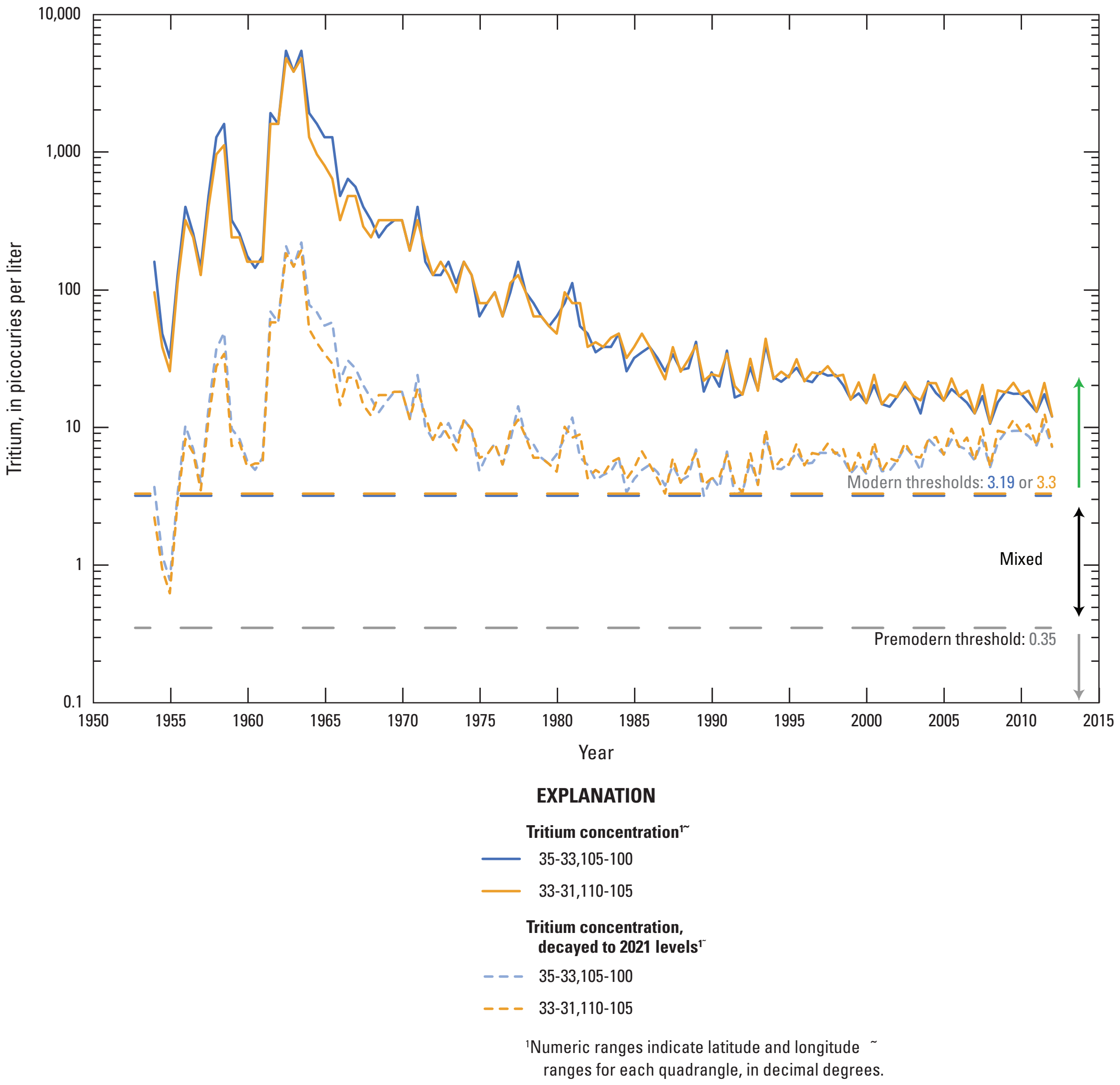


Figure 12. Tritium concentrations for precipitation interpolated by Michel and others (2018) and Jurgens (2018) for two latitude and longitude quadrangles in New Mexico.

Table 19. Per- and polyfluoroalkyl substance concentrations from surface-water diversion samples with values above the laboratory detection level, including repeat sampling after detection.

[Values are reported in nanograms per liter. Values in italics represent estimated concentrations greater than the laboratory detection level and less than the laboratory reporting level in effect at the time of sample analysis. --, below the laboratory detection level]

Report identification number	Perfluoroalkylcarboxylic acids							Perfluoroalkyl sulfonic acids				Fluorotelomer sulfonates
	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFBS	PFPeS	PFHxS	PFOS	6:2FTS
75	--	--	--	--	--	--	--	--	--	--	*0.96*	--
94	--	--	--	--	--	--	--	--	--	*1.5*	--	--
95	--	--	--	--	--	--	--	--	--	*1.3*	--	--

which is immediately downstream from Albuquerque, the largest urban area in New Mexico. Compared with upstream sites, this site had much higher concentrations of PFAS that were highly variable, with totals ranging from 8.7 to 155.4 ng/L and detections of PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFBS, PFHxS, PFOS, and (or) PFOSA (fig. 13*C*). Rio Grande Floodway was sampled in August of 2020 and 2021 and had elevated concentrations (15.8 and 29.7 ng/L total PFAS) compared with the average surface-water sample concentrations throughout the State and had detections of multiple PFAS: PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFBS, PFHxS, and PFOS. Rio Grande El Paso consistently had some of the highest PFAS concentrations in surface-water samples from this study (ranging from 13 to 86.1 ng/L total PFAS) (fig. 13*D*). No releases of water from Elephant Butte Reservoir to the Rio Grande occurred between October 3, 2020, and May 18, 2021, as shown by USGS streamgage 0861000 Rio Grande below Elephant Butte Dam, N. Mex. (USGS, 2022b). The total PFAS concentration (ranging from 38.1 to 85.5 ng/L) for Rio Grande El Paso was highest for samples collected during this period—between October 15, 2020, and May 14, 2021—and 6:2FTS and PFPeS were present only during this time (fig. 13*D*). PFHpA was present in the water samples from this time period and in two more samples collected in July and August 2021 after releases from Elephant Butte Reservoir had resumed (fig. 13*D*). Other compounds found at Rio Grande El Paso were PFBA, PFPeA, PFHxA, PFOA, PFBS, PFHxS, and PFOS.

The second longest river sampled was the Pecos River, and samples collected there showed a similar progressive increase in PFAS downstream as observed in the Rio Grande samples. Pecos Puerto de Luna generally had no PFAS detections, with only one of seven sampling events having a detection greater than the detection level with 2.8 ng/L total PFAS, including PFOA and PFPeA. Pecos Artesia had higher concentrations and more PFAS than observed upstream at Pecos Puerto de Luna (fig. 13*E*). Total PFAS concentrations ranged from 3.9 to 24.9 ng/L, with PFBA, PFBS, PFHxA, PFHxS, PFOA, PFOS, and PFPeA detected in four to seven samples and PFHpA detected only in one sample. Pecos Red Bluff was sampled only once in August 2020 and had similar compounds to those found near Artesia, with a total PFAS concentration of 7.5 ng/L, including PFBA, PFHxA, PFHxS, PFOS, and PFPeA.

The San Juan River was sampled near Archuleta, N. Mex. (San Juan Archuleta), and then downstream from Farmington, N. Mex., at San Juan Fruitland, downstream of the confluence of the Animas and San Juan Rivers. San Juan Archuleta PFAS concentrations were below the detection level for three samples but were as much as 4.4 ng/L total PFAS in the other five samples, with only PFBA, PFPeA, and (or) PFBS present (fig. 13*F*). Animas Farmington had slightly higher PFAS concentrations than upstream sites, with values as much as 7.3 ng/L total PFAS and PFPeA, PFHxA, PFBS, PFHxS, and (or) PFOS present in all but one of seven samples (fig. 13*G*). San Juan Fruitland was similarly variable, with generally low-level total PFAS (as much as 7.7 ng/L) and PFBA, PFPeA, PFHxA, PFBS, and (or) PFOSA present in all but two of nine samples (fig. 13*H*).

The Canadian River was sampled at three locations: Canadian Sanchez, Canadian Conchas, and Canadian Logan. The samples collected from Canadian Sanchez and Canadian Conchas in September 2020 had the highest total PFAS concentrations among samples at these sites, with as much as 16.4 ng/L total PFAS at Canadian Sanchez and 10.5 ng/L total PFAS at Canadian Conchas and detections of PFBA, PFBS, and PFOS at both locations; Canadian Sanchez also had a low-level detection of PFPeA, and the Canadian Conchas had a low-level detection of PFHpA. Canadian Logan had lower total PFAS concentrations than upstream sites (ranging from 1 to 4.9 ng/L) and included detections of PFBA, PFBS, and PFOS.

Several sites on smaller rivers throughout the State were sampled only a few times to get a general sense for concentrations and the potential need for more focused sampling. Streamflow at Rio Puerco Bernardo is ephemeral and occurs as a response to precipitation events. Two samples were collected from this site, one in September 2020 and the other in July 2021. Total PFAS concentrations were high at this site (35.7 and 38.6 ng/L) compared with other surface-water sites in the study and comprised PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFBS, and (or) PFOS. Streamflow at Rio Puerco Bernardo had a sharp increase in flow, followed by a slower recession during these sampling events. Collecting samples throughout the hydrograph (that is, at several times that reflect changing flow conditions) could enhance understanding of PFAS fluctuation at this site.

Rio Chama Abiquiu was sampled four times throughout the study during different seasons (August and November 2020, and February and April 2021; fig. 13*I*). Total PFAS concentrations were low at this site (1.7 to 4 ng/L), and quantified detections were all between the detection and reporting levels. The sample from April 9, 2021, had no PFAS detected. PFBS was detected in the other three samples, and PFBA was detected in the samples from November 2020 and February 2021.

Gila River had high total PFAS (53 and 19 ng/L) compared with the other surface-water sites in the study. Only two samples were collected at this site, during September of 2020 and 2021, and more sampling at this site could help to identify the time periods over which elevated concentrations occur and to characterize variability. The sample from September 2020 had PFBA, PFPeA, PFHxA, PFHpA, and PFBS, whereas the sample from September 2021 had only PFBA and PFBS.

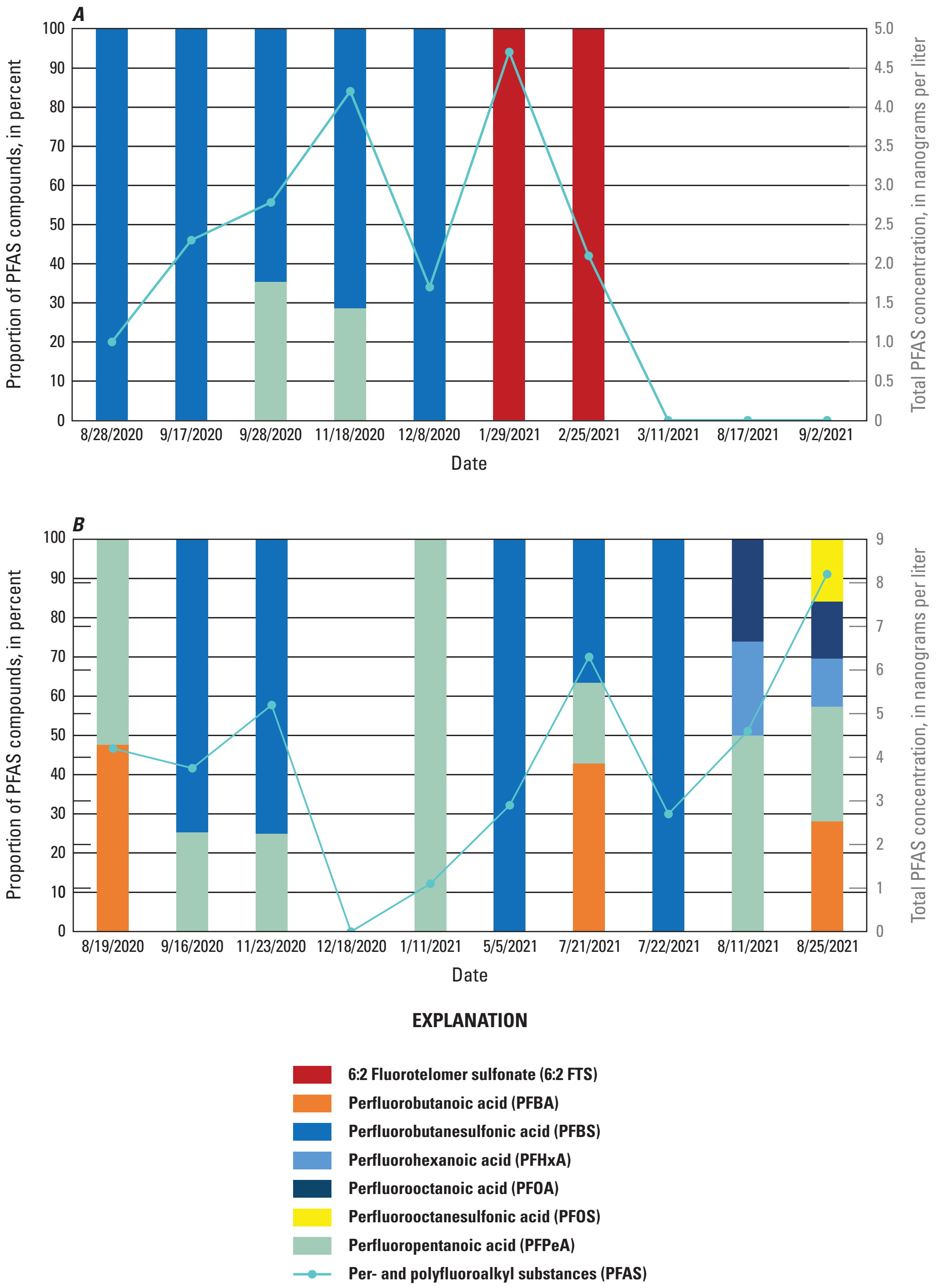


Figure 13. For per- and polyfluoroalkyl substances (PFAS) with detectable concentrations, total concentrations, and proportions of total concentrations contributed by individual PFAS for *A*, Rio Grande above Buckman Diversion near White Rock, New Mexico; *B*, Rio Grande at Alameda Bridge at Alameda, N. Mex.; *C*, Rio Grande at Valle de Oro, N. Mex.; *D*, Rio Grande at El Paso, Texas; *E*, Pecos River near Artesia, N. Mex.; *F*, San Juan River near Archuleta, N. Mex.; *G*, Animas River at Farmington, N. Mex.; *H*, San Juan River near Fruitland, N. Mex.; and *I*, Rio Chama below Abiquiu Dam, N. Mex.

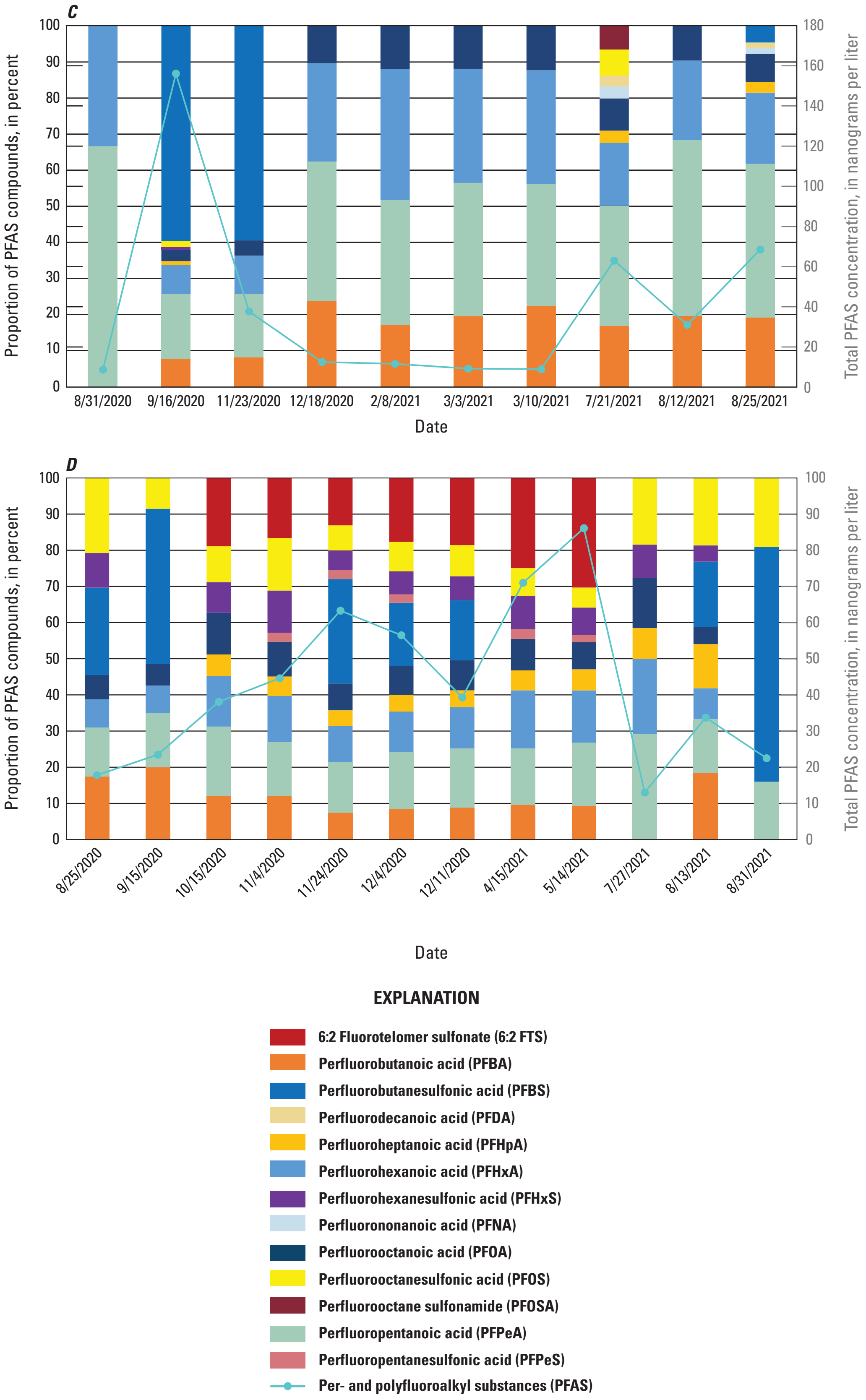


Figure 13.—Continued

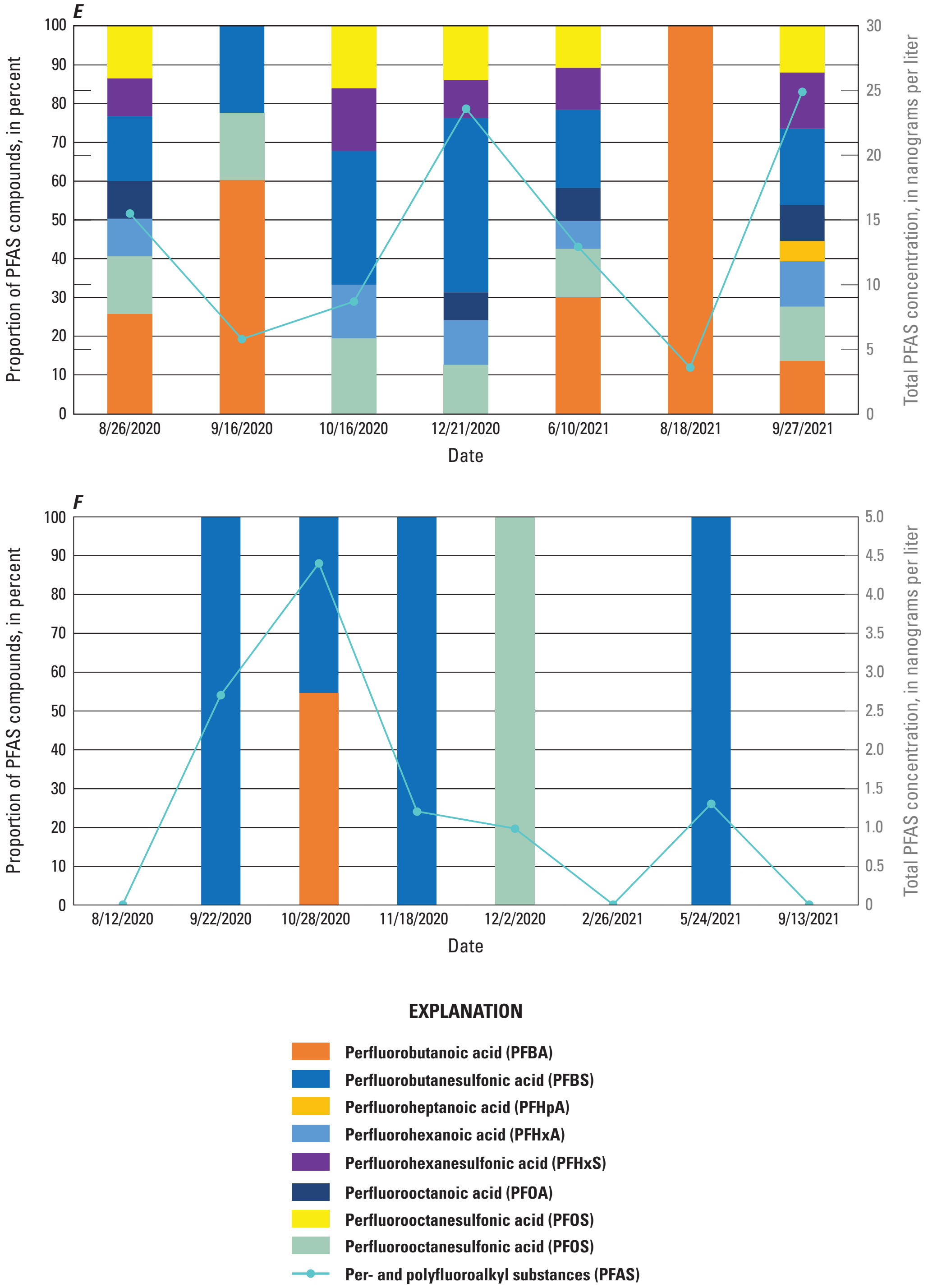


Figure 13.—Continued

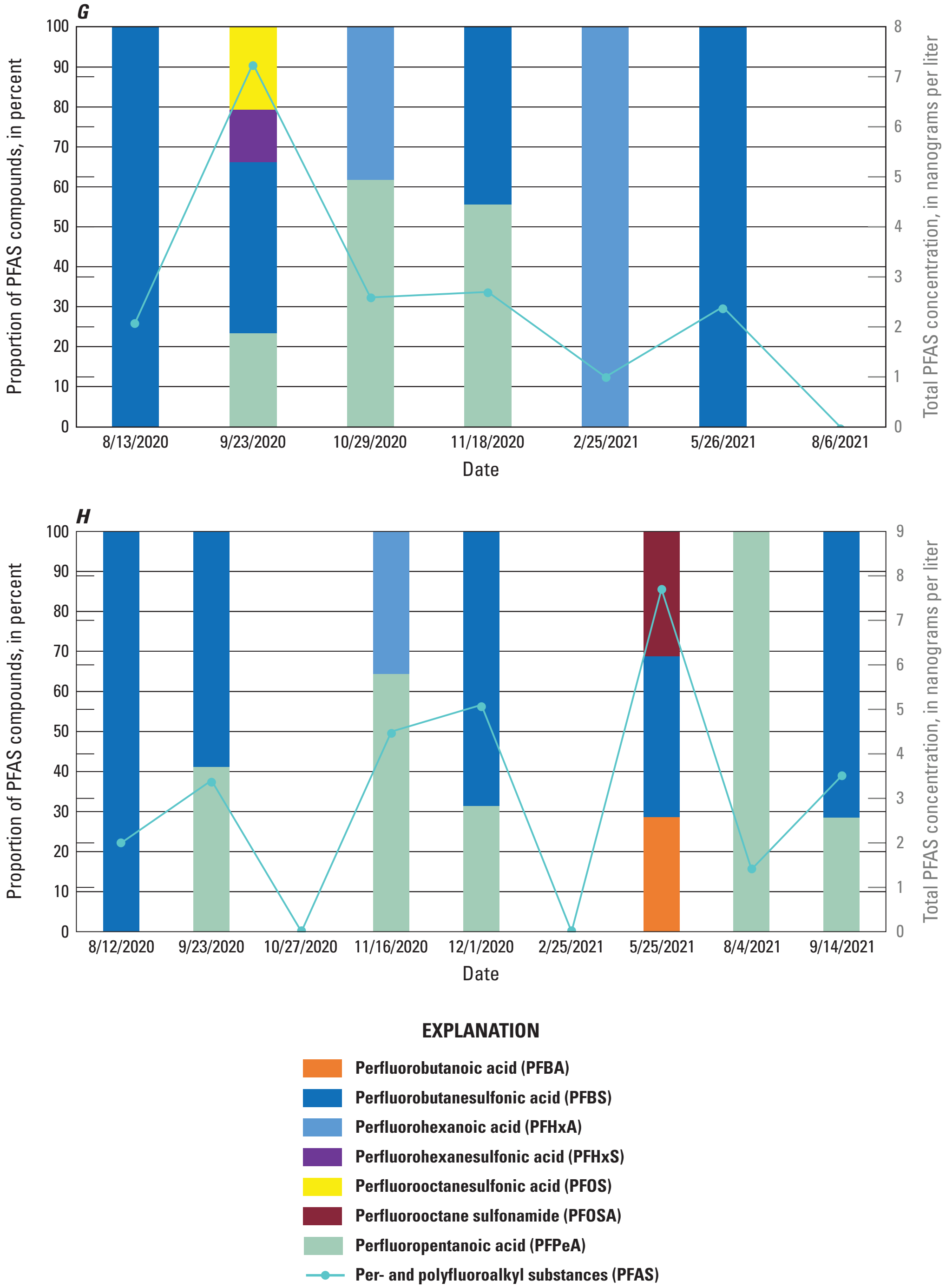


Figure 13.—Continued

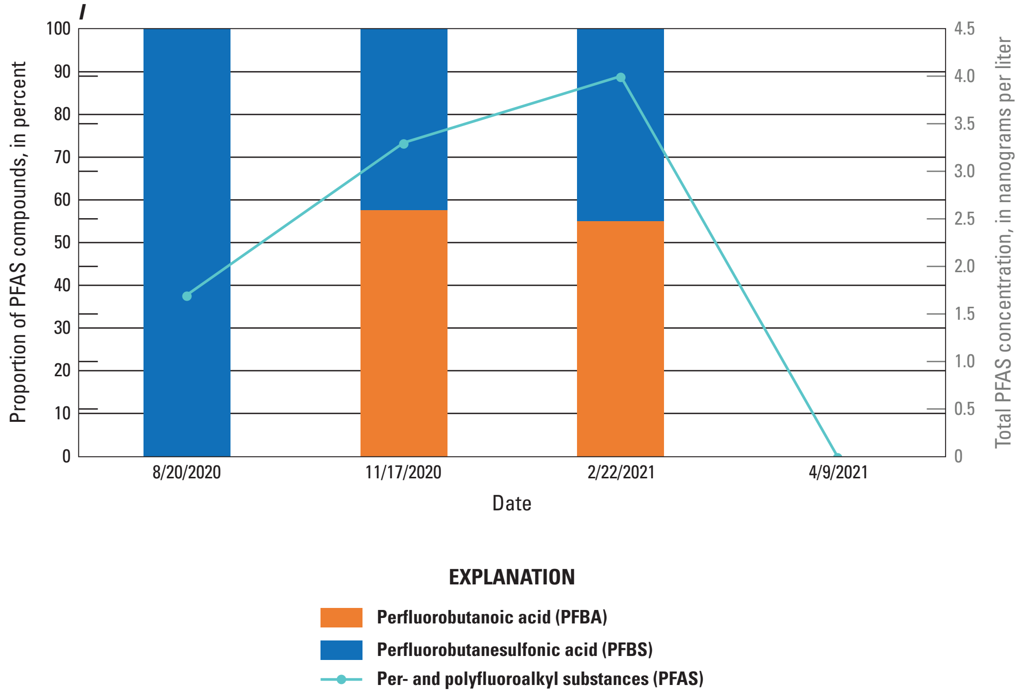


Figure 13.—Continued

Per- and Polyfluoroalkyl Substance Fluxes

The instantaneous PFAS loading rate, or flux, was calculated for each sampling event, as described in the "Methods" section, and results are presented in table 20. These fluxes are only representative of the time they were collected, and they may not be representative of fluxes during previous years or fluxes after the sampling event. Samples were collected during stable flow when possible, and associated streamflow hydrographs are provided in figure 14*A–F* for reference. Rio Grande Valle de Oro and Rio Grande El Paso had the highest observed fluxes, 37.76 and 65.58 g/d, respectively (fig. 14*A*, *B*). These sites also had the highest average load when all fluxes were averaged for each location, with Rio Grande Valle de Oro averaging 16.17 g/d and Rio Grande El Paso averaging 17.13 g/d. San Juan Fruitland, Rio Grande Buckman, and Rio Grande Alameda had elevated averages compared with the average values from surface-water sites in the State (between 2 and 5 g/d; (fig. 14*D–F*). The rest of the sample locations had average fluxes of less than 2 g/d. Only two samples were collected at the Gila River site, but the site had high fluxes (11.09 and 10.04 g/d) (fig. 14*C*).

Per- and Polyfluoroalkyl Substances and Land Cover

Relations between near-site watershed land cover categories (table 3) and total PFAS concentrations were evaluated. Sites sampled frequently (more than five times) with more than 30 percent developed land cover had higher total PFAS concentrations than areas with predominantly mixed or undeveloped land cover, with a median value of 35.2 ng/L. Sites categorized as mixed and sampled frequently had a median total PFAS concentration of 2.7 ng/L, and the undeveloped category for frequently sampled sites had a median of 1.25 ng/L. No developed sites were sampled infrequently (less than five times). Mixed sites sampled infrequently had a median total PFAS concentration of 4.8 ng/L, and undeveloped sites had a median of 4.3 ng/L. The higher median value at undeveloped sites sampled infrequently was due to several outliers for the total PFAS concentration, including Gila River with 53.5 ng/L, Rio Puerco Bernardo with 38.6 and 35.7 ng/L, and Rio Grande Floodway with 29.7 ng/L. Outliers in the undeveloped category for frequently sampled sites included Pecos Artesia with 24.9, 15.5, and 12.9 ng/L. These outliers show that PFAS can be found at sites without any major development, as only one of these sites (Pecos Artesia) is downstream from a NPDES outfall (table 4) or has other direct evidence of potential PFAS sources within the near-site watershed (table 6).

Table 20. Per- and polyfluoroalkyl substance (PFAS) instantaneous fluxes at surface-water sampling locations with PFAS detections.

[Dates shown as month, day, year. USGS, U.S. Geological Survey; ID, identifier; N. Mex., New Mexico; Tex., Texas; R, river; NA, not available]

USGS site number	Site name	Sample date and time	Total PFAS concentration (nanograms per liter)	Streamflow date and time	Instantaneous streamflow (cubic feet per second)	PFAS instantaneous flux (grams per day)
07221500	Canadian River near Sanchez, N. Mex.	9/2/2020 13:35	16.83	9/2/2020 13:30	2.36	0.10
07221500	Canadian River near Sanchez, N. Mex.	5/10/2021 14:30	4.6	5/10/2021 14:30	1.07	0.01
07224500	Canadian River below Conchas Dam, N. Mex.	9/29/2020 12:35	10.5	NA	NA	NA
07227000	Canadian River at Logan, N. Mex.	11/30/2020 14:10	0.95	11/30/2020 14:15	4.39	0.01
07227000	Canadian River at Logan, N. Mex.	5/6/2021 13:05	4.9	5/6/2021 13:00	2.00	0.02
07227000	Canadian River at Logan, N. Mex.	8/2/2021 13:50	4.79	8/2/2021 13:45	2.37	0.03
08287000	Rio Chama below Abiquiu Dam, N. Mex.	8/20/2020 12:00	1.7	8/20/2020 12:00	718.82	2.99
08287000	Rio Chama below Abiquiu Dam, N. Mex.	11/17/2020 12:30	3.3	11/17/2020 12:30	74.86	0.60
08287000	Rio Chama below Abiquiu Dam, N. Mex.	2/22/2021 12:30	4	2/22/2021 12:30	33.86	0.33
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	8/28/2020 13:00	1	8/28/2020 13:00	818.30	2.00
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	9/17/2020 12:00	2.3	9/17/2020 12:00	686.26	3.86
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	9/28/2020 12:00	2.78	9/28/2020 12:00	529.95	3.60
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	11/12/2020 14:30	4.2	11/12/2020 14:30	392.63	4.03
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	12/8/2020 14:00	1.7	12/8/2020 14:00	524.01	2.18
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	1/29/2021 12:30	4.7	1/29/2021 12:30	525.21	6.04
08313150	Rio Grande above Buckman Diversion, near White Rock, N. Mex.	2/25/2021 11:00	2.1	2/25/2021 11:00	591.05	3.04
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	8/19/2020 11:05	4.2	8/19/2020 11:00	287.54	2.96
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	9/16/2020 11:00	3.75	9/16/2020 11:00	186.12	1.71
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	11/23/2020 14:00	5.2	11/23/2020 14:00	411.55	5.24
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	1/11/2021 10:35	1.1	1/11/2021 10:30	511.39	1.38
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	5/5/2021 12:05	2.9	5/5/2021 12:00	1,282.92	9.10
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	7/21/2021 9:00	6.3	7/21/2021 9:00	180.26	2.78
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	7/22/2021 9:00	2.7	7/22/2021 9:00	157.93	1.04
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	8/11/2021 10:35	4.6	8/11/2021 10:30	271.55	3.06
08329918	Rio Grande at Alameda Bridge at Alameda, N. Mex.	8/25/2021 10:00	8.2	8/25/2021 10:00	99.13	1.99
08330830	Rio Grande at Valle De Oro, N. Mex.	8/31/2020 10:25	8.7	8/31/2020 10:30	249.58	5.31

Table 20. Per- and polyfluoroalkyl substance (PFAS) instantaneous fluxes at surface-water sampling locations with PFAS detections.—Continued

[Dates shown as month, day, year. USGS, U.S. Geological Survey; ID, identifier; N. Mex., New Mexico; Tex., Texas; R, river; NA, not available]

USGS site number	Site name	Sample date and time	Total PFAS concentration (nanograms per liter)	Streamflow date and time	Instantaneous streamflow (cubic feet per second)	PFAS instantaneous flux (grams per day)
08330830	Rio Grande at Valle De Oro, N. Mex.	9/16/2020 13:00	156.1	9/16/2020 13:00	98.85	37.76
08330830	Rio Grande at Valle De Oro, N. Mex.	11/23/2020 17:00	37.7	NA	NA	NA
08330830	Rio Grande at Valle De Oro, N. Mex.	12/18/2020 15:00	12.5	NA	NA	NA
08330830	Rio Grande at Valle De Oro, N. Mex.	2/8/2021 14:00	11.6	2/8/2021 14:00	446.22	12.67
08330830	Rio Grande at Valle De Oro, N. Mex.	3/3/2021 12:30	9.6	3/3/2021 12:30	471.39	11.07
08330830	Rio Grande at Valle De Oro, N. Mex.	3/10/2021 11:30	8.9	3/10/2021 11:30	550.60	11.99
08330830	Rio Grande at Valle De Oro, N. Mex.	6/23/2021 11:30	19.8	6/23/2021 11:30	346.58	16.79
08330830	Rio Grande at Valle De Oro, N. Mex.	7/21/2021 14:00	49.5	7/21/2021 14:00	232.84	28.20
08330830	Rio Grande at Valle De Oro, N. Mex.	7/22/2021 13:00	28.5	7/22/2021 13:00	197.00	13.74
08330830	Rio Grande at Valle De Oro, N. Mex.	8/12/2021 14:00	34	8/12/2021 14:00	196.14	16.32
08330830	Rio Grande at Valle De Oro, N. Mex.	8/25/2021 11:30	43.1	8/25/2021 11:30	74.06	7.81
08330830	Rio Grande at Valle De Oro, N. Mex.	8/25/2021 18:00	68.5	8/25/2021 18:00	96.90	16.24
08353000	Rio Puerco near Bernardo, N. Mex.	9/13/2020 18:05	35.7	9/13/2020 18:00	21.2	1.85
08353000	Rio Puerco near Bernardo, N. Mex.	7/26/2021 12:00	38.6	7/26/2021 12:00	56.3	5.32
08358400	Rio Grande Floodway at San Marcial, N. Mex.	8/24/2020 12:35	15.8	8/24/2020 12:30	18.10	0.70
08358400	Rio Grande Floodway at San Marcial, N. Mex.	8/12/2021 14:00	29.7	8/12/2021 13:30	0.58	0.04
08364000	Rio Grande at El Paso, Tex.	8/25/2020 9:35	17.8	NA	NA	NA
08364000	Rio Grande at El Paso, Tex.	9/15/2020 11:05	23.5	9/15/2020 11:00	482.54	27.75
08364000	Rio Grande at El Paso, Tex.	10/15/2020 15:05	38.1	10/15/2020 15:00	91.92	8.57
08364000	Rio Grande at El Paso, Tex.	11/4/2020 13:30	44.6	11/4/2020 13:30	84.06	9.17
08364000	Rio Grande at El Paso, Tex.	11/24/2020 12:00	63.3	NA	NA	NA
08364000	Rio Grande at El Paso, Tex.	12/4/2020 12:35	56.5	12/4/2020 12:30	80.72	11.16
08364000	Rio Grande at El Paso, Tex.	12/11/2020 12:35	39.3	12/11/2020 12:30	83.78	8.06
08364000	Rio Grande at El Paso, Tex.	4/15/2021 10:35	71	4/15/2021 10:30	12.89	2.24
08364000	Rio Grande at El Paso, Tex.	5/14/2021 9:35	86.1	5/14/2021 9:30	5.62	1.18
08364000	Rio Grande at El Paso, Tex.	7/27/2021 8:55	13	7/27/2021 9:00	546.67	17.39
08364000	Rio Grande at El Paso, Tex.	8/13/2021 10:35	35.2	8/13/2021 10:30	761.44	65.58
08364000	Rio Grande at El Paso, Tex.	8/31/2021 9:05	22.5	8/31/2021 9:00	366.91	20.20
08383500	Pecos River near Puerto de Luna, N. Mex.	6/8/2021 14:00	2.8	6/8/2021 14:00	69.30	0.47
08396500	Pecos River near Artesia, N. Mex.	8/26/2020 13:35	15.5	8/26/2020 13:15	24.47	0.93
08396500	Pecos River near Artesia, N. Mex.	9/16/2020 10:30	5.8	9/16/2020 10:30	47.20	0.67

Table 20. Per- and polyfluoroalkyl substance (PFAS) instantaneous fluxes at surface-water sampling locations with PFAS detections.—Continued

[Dates shown as month, day, year. USGS, U.S. Geological Survey; ID, identifier; N. Mex., New Mexico; Tex., Texas; R, river; NA, not available]

USGS site number	Site name	Sample date and time	Total PFAS concentration (nanograms per liter)	Streamflow date and time	Instantaneous streamflow (cubic feet per second)	PFAS instantaneous flux (grams per day)
08396500	Pecos River near Artesia, N. Mex.	10/16/2020 7:40	8.7	10/16/2020 7:45	18.96	0.40
08396500	Pecos River near Artesia, N. Mex.	12/21/2020 13:30	23.6	12/21/2020 13:30	48.24	2.79
08396500	Pecos River near Artesia, N. Mex.	6/10/2021 9:00	12.93	6/10/2021 9:00	77.38	2.45
08396500	Pecos River near Artesia, N. Mex.	8/18/2021 12:00	3.6	8/18/2021 12:00	242.75	2.14
08396500	Pecos River near Artesia, N. Mex.	9/27/2021 13:30	24.9	9/27/2021 13:30	33.26	2.03
08407500	Pecos River at Red Bluff, N. Mex.	8/26/2020 9:05	7.5	8/26/2020 9:00	29.55	0.54
09355500	San Juan River near Archuleta, N. Mex.	9/22/2020 14:30	2.7	9/22/2020 14:30	742.74	4.91
09355500	San Juan River near Archuleta, N. Mex.	10/28/2020 12:30	4.4	10/28/2020 12:30	508.73	5.48
09355500	San Juan River near Archuleta, N. Mex.	11/18/2020 13:35	1.2	11/18/2020 13:30	319.61	0.94
09355500	San Juan River near Archuleta, N. Mex.	12/2/2020 15:30	0.98	12/2/2020 15:30	367.10	0.88
09355500	San Juan River near Archuleta, N. Mex.	5/24/2021 15:50	1.3	5/24/2021 15:45	323.91	1.03
09364500	Animas River at Farmington, N. Mex.	8/13/2020 15:35	2.1	8/13/2020 15:30	38.55	0.20
09364500	Animas River at Farmington, N. Mex.	9/23/2020 17:00	7.26	9/23/2020 17:00	50.97	0.91
09364500	Animas River at Farmington, N. Mex.	10/29/2020 9:30	2.59	10/29/2020 9:30	208.99	1.32
09364500	Animas River at Farmington, N. Mex.	11/18/2020 10:00	2.7	11/18/2020 10:00	191.45	1.26
09364500	Animas River at Farmington, N. Mex.	2/25/2021 16:15	1	2/25/2021 16:15	164.47	0.40
09364500	Animas River at Farmington, N. Mex.	5/26/2021 10:45	2.4	5/26/2021 10:45	1,091.82	6.41
09367540	San Juan R near Fruitland, N. Mex.	8/12/2020 16:05	2	8/12/2020 16:00	572.88	2.80
09367540	San Juan R near Fruitland, N. Mex.	9/23/2020 10:35	3.4	9/23/2020 10:30	621.63	5.17
09367540	San Juan R near Fruitland, N. Mex.	11/16/2020 15:30	4.5	11/16/2020 15:30	511.93	5.64
09367540	San Juan R near Fruitland, N. Mex.	12/1/2020 16:00	5.1	12/1/2020 16:00	524.12	6.54
09367540	San Juan R near Fruitland, N. Mex.	5/25/2021 10:35	5.3	5/25/2021 10:30	1,336.55	17.33
09367540	San Juan R near Fruitland, N. Mex.	8/4/2021 11:35	1.4	8/4/2021 11:30	780.09	2.67
09367540	San Juan R near Fruitland, N. Mex.	9/14/2021 9:05	3.5	9/14/2021 9:00	438.80	3.76
09430500	Gila River near Gila, N. Mex.	9/10/2020 10:35	53.54	9/10/20 10:30	84.67	11.09
09430500	Gila River near Gila, N. Mex.	9/8/2021 9:30	21.9	9/8/21 9:30	187.32	10.04

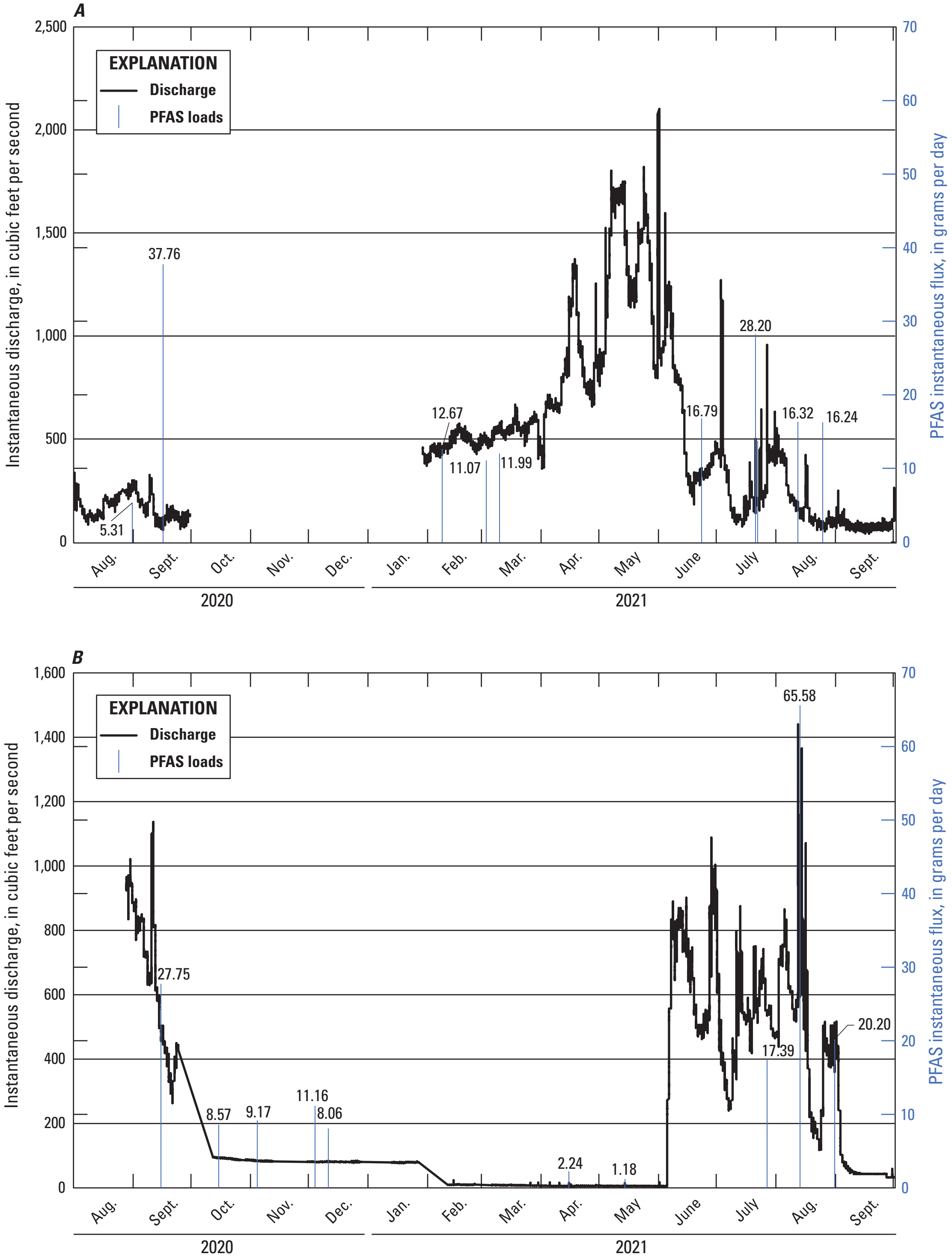


Figure 14. Total per- and polyfluoroalkyl substance (PFAS) instantaneous fluxes at surface-water sampling locations across New Mexico. *A*, Rio Grande at Valle de Oro, New Mexico; *B*, Rio Grande at El Paso, Texas; *C*, Gila River near Gila, N. Mex.; *D*, San Juan River near Fruitland, N. Mex.; *E*, Rio Grande above Buckman Diversion near White Rock, N. Mex.; and *F*, Rio Grande at Alameda Bridge at Alameda, N. Mex.

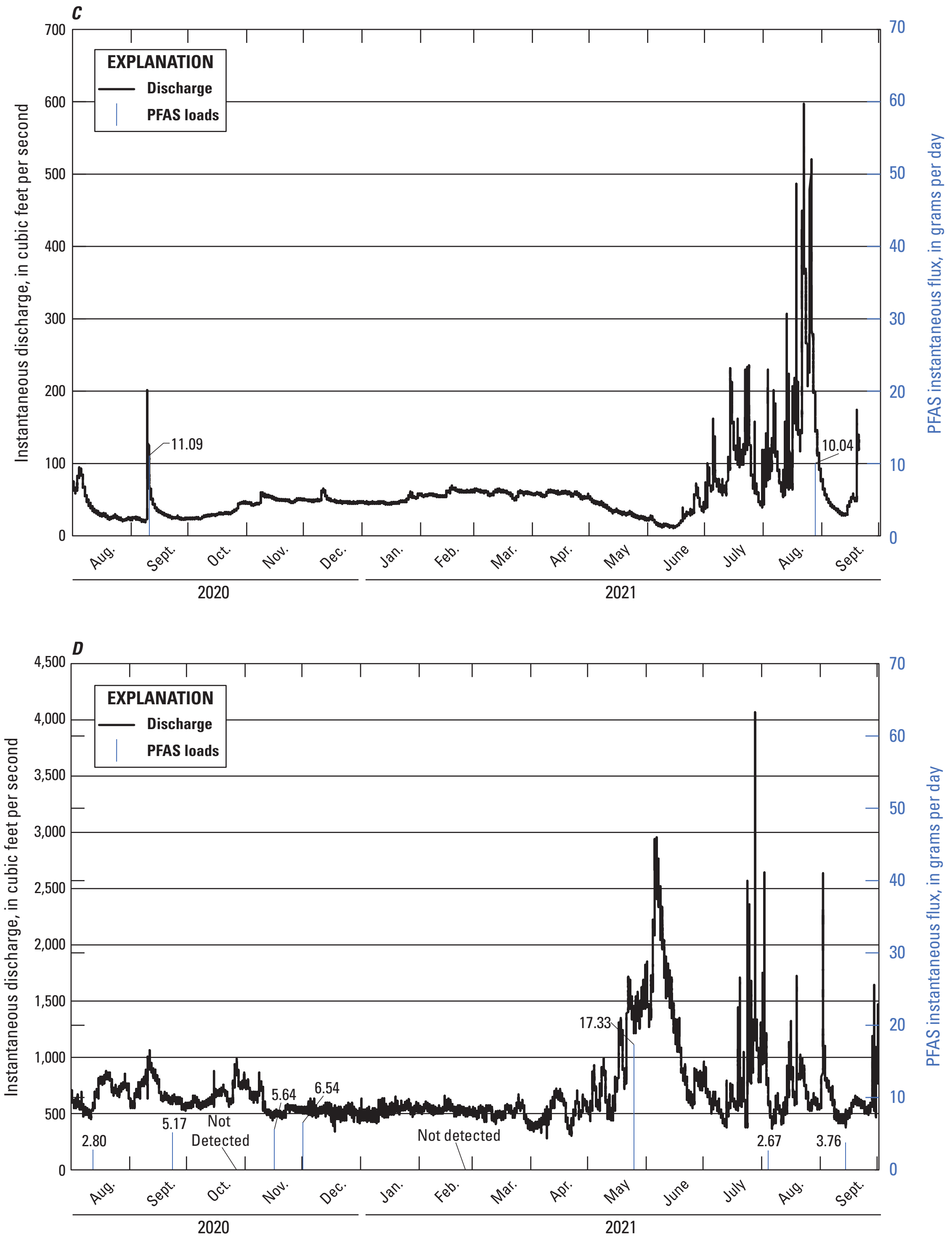


Figure 14.—Continued

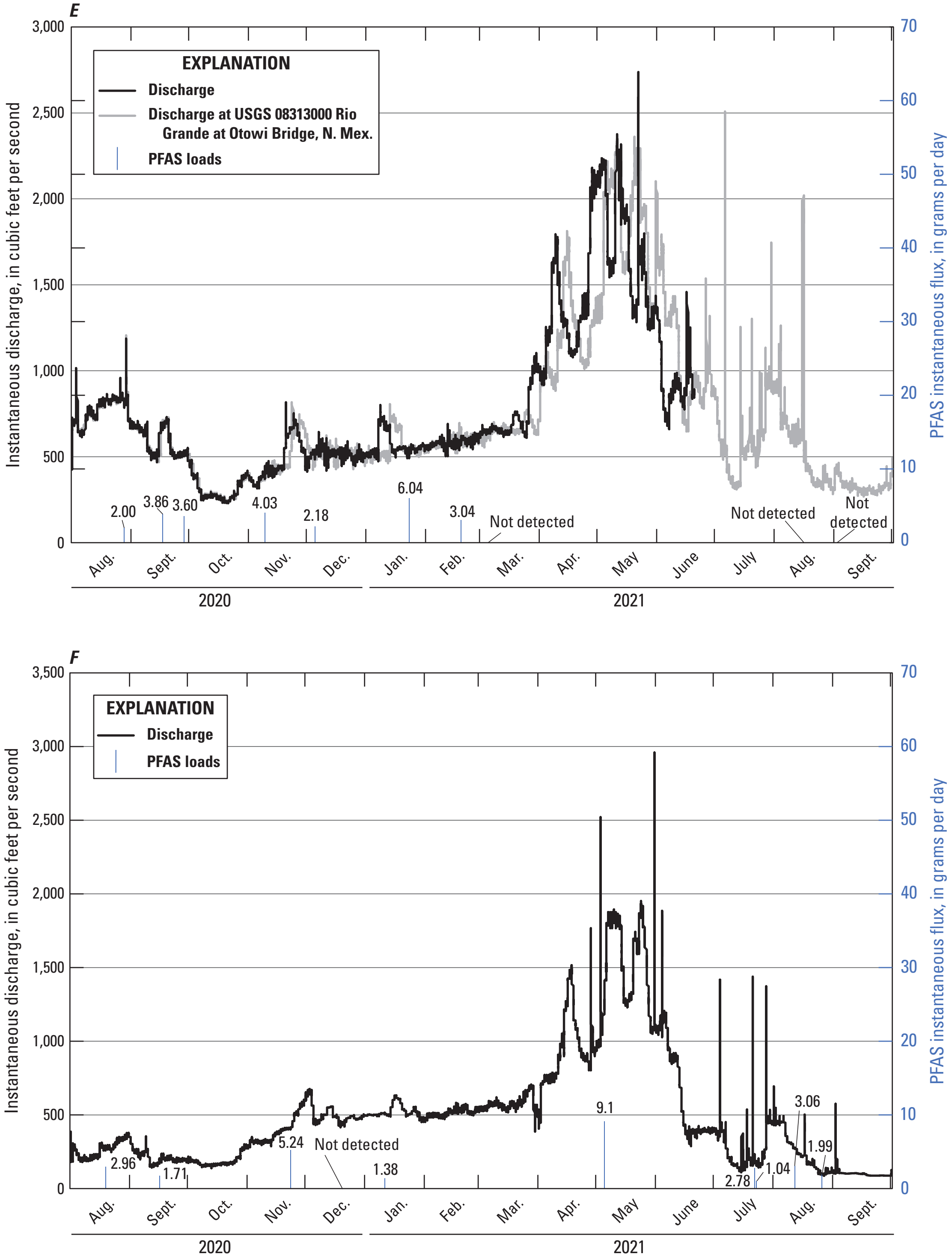


Figure 14.—Continued

Field Properties

The field properties water temperature, pH, specific conductance, and dissolved oxygen were measured onsite prior to sample collection. Water temperature ranged from 1.5 to 32.7 °C and varied depending on the time of year the sample was collected. Field pH values ranged from 6.9 to 10.0, with the highest pH recorded at San Juan Archuleta. Specific conductance ranged from 213 to 13,200 µS/cm, with the average specific conductance notably higher at Canadian Logan (12,525 µS/cm) than at other sites. Dissolved-oxygen concentrations ranged from 5.0 to 14.8 mg/L, with the highest concentration observed at San Juan Archuleta and the lowest observed at Canadian Conchas Dam.

Wastewater Chemistry

Seven surface-water sites across New Mexico were sampled and analyzed for wastewater tracer compounds to help characterize potential water-quality impacts resulting from nearby anthropogenic activities. The sites sampled were sites that were not visited for other water-quality sampling during the study period: Rio Chama Abiquiu, Rio Grande Buckman, Rio Grande Alameda, Pecos Puerto de Luna, Pecos Artesia, San Juan Archuleta, and Animas Farmington (fig. 15). The 37 synthetic organic chemicals in the wastewater tracer suite originate from multiple anthropogenic sources, including domestic and industrial wastewater discharge and surface runoff from agricultural sources such as livestock and cultivated crops. A list of these wastewater tracers, their constituent class, and their probable environmental source(s) are shown in table 21. Appendix 1, table 1.3, summarizes the surface-water detections and concentrations for wastewater tracer compounds.

Rio Grande Alameda had a total wastewater tracer concentration ranging from 0.34 to 0.80 µg/L with the following seven wastewater tracer compounds present, the most of any site: bisphenol A, carbamazepine, coprostanol, N,N-diethyl-meta-toluamide (DEET), 4-NP1EO, 4-NP2EO, and 4-t-OP1EO (fig. 15*C*). Rio Chama Abiquiu had a total wastewater tracer concentration ranging from not detected to 1.16 µg/L with six compounds present, including bisphenol A, DEET, 4-methylphenol, 4-NP2EO, and 4-t-OP1EO (fig. 15*A*). Rio Grande Buckman had a total wastewater concentration ranging from not detected to 1.23 µg/L, with six compounds present, namely bisphenol A, coprostanol, DEET, triclosan, 4-NP1EO, and 4-NP2EO (fig. 15*B*). Pecos Artesia had a total wastewater tracer concentration ranging from not detected to 1.64 µg/L (fig. 15*E*), which was the highest total wastewater concentration observed, and had seven compounds present, namely bisphenol A, carbamazepine, coprostanol, 3,4-Dichloroaniline, 4-NP1EO, 4-NP2EO, and 4-t-OP1EO. Pecos Puerto de Luna, Animas Farmington, and San Juan Archuleta all had five or fewer compounds detected (fig. 15*D*, *F*, *G*).

The higher overall concentrations and greater numbers of detections at some sites (Rio Grande Buckman, Rio Grande Alameda, and Pecos Artesia) might be associated with the relatively higher densities of urban infrastructure nearby, such as waste management facilities, airports, and other industrial manufacturing shown in table 6. All sites show some temporal variation in concentrations measured.

Dissolved Organic Carbon

DOC was detected at low concentrations in the majority of surface-water samples, with an average concentration of 1.84 mg/L. The highest DOC concentration was 3.4 mg/L at Rio Chama Abiquiu, which averaged 2.7 mg/L from five sampling events. Pecos River Artesia and Pecos Puerto de Luna had lower DOC concentrations compared to the rest of the sites.

Major and Trace Elements

The same seven surface-water sites analyzed for wastewater tracers were also sampled and analyzed for major/minor elements, trace elements, and REEs. Principal components analysis was conducted to characterize chemical composition of surface-water sites using Spearman-ranked trace-element data, which reduced dimensionality. The principal components analysis (fig. 16) separates the samples relative to five predominant analyte groups characterized by higher levels of (1) specific conductance, certain major/minor elements (calcium [Ca], boron [B], and lithium [Li]), and the ratio of Gd measured in the sample to background Gd ($Gd/Gd_{background}$); (2) trace elements (iron [Fe], copper [Cu], and lead [Pb]) and REEs (lanthanum [La] and sum of REEs); (3) uranium (U) and potassium (K); (4) molybdenum (Mo) and cadmium (Cd); and (5) arsenic (As), vanadium (V), and silicon dioxide (SiO_2), as depicted in figure 16*B*. The first principal component accounted for 44 percent of the dataset variability and was driven by differences in characteristics between water groups 1 and 2, and the second principal component represented 20 percent of the variability.

Chemical compositions for samples from Pecos Puerto de Luna and Pecos Artesia plot in locations on figure 16*A* that indicate relatively high conductivity and major-element concentrations (water group 1). Samples from Pecos Artesia are additionally characterized by relatively high concentrations of U and K (water group 3).

Samples from Rio Grande Alameda and Rio Grande Buckman generally included relatively high concentrations of As, Cd, Mo, SiO_2, and V (similar to water groups 4 and 5). However, samples collected at Rio Grande Buckman from August 28, 2020, to September 24, 2020, plotted near samples from the Rio Chama Abiquiu (fig. 16*A*), which are characterized by relatively high concentrations of trace elements and REEs (water group 2).

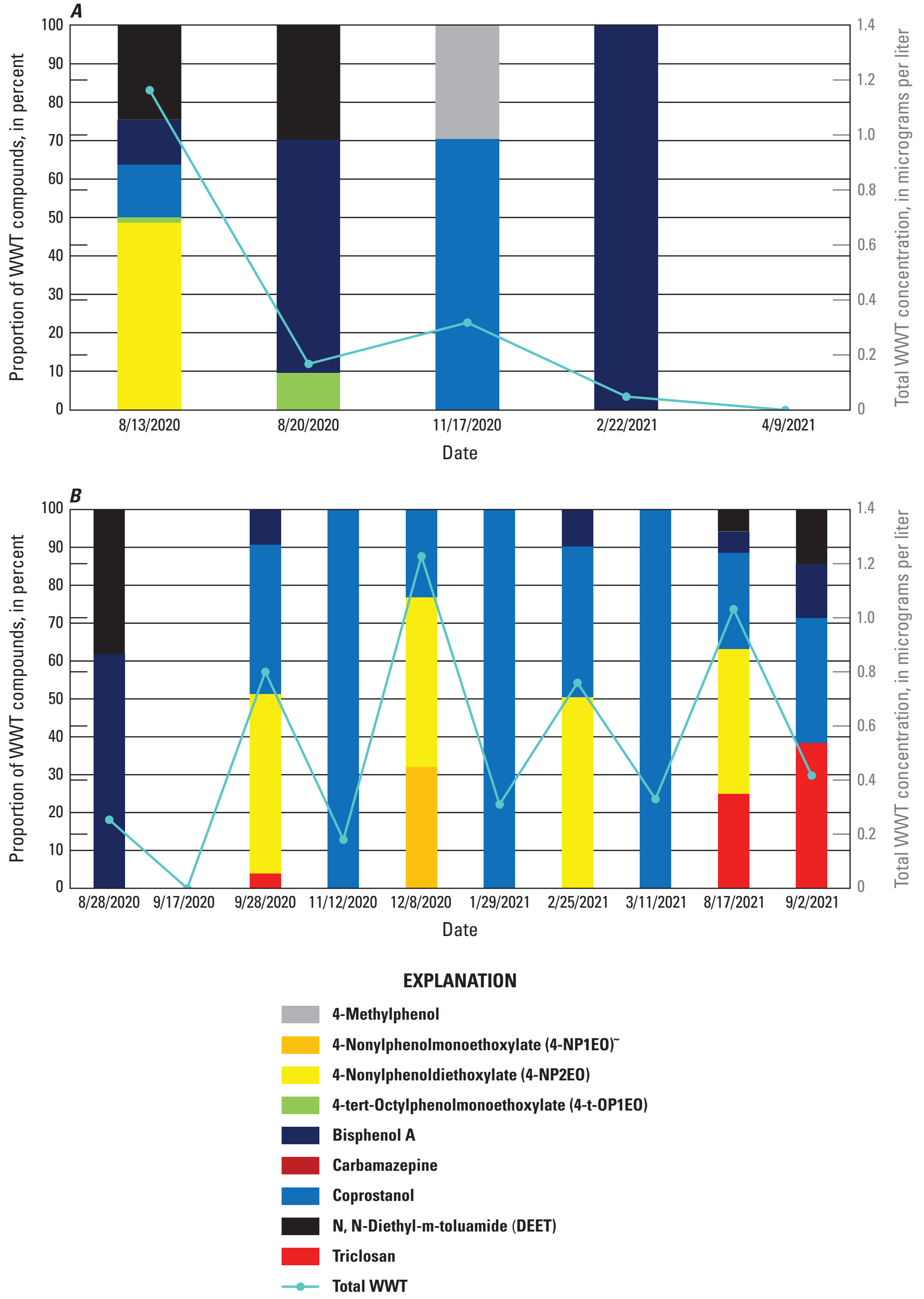


Figure 15. Proportion of wastewater tracer (WWT) compounds and total wastewater compound concentrations in surface-water samples with multiple compound detectable concentrations at *A*, Rio Chama near Abiquiu Dam, New Mexico; *B*, Rio Grande above Buckman Diversion near White Rock, N. Mex.; *C*, Rio Grande at Alameda Bridge at Alameda, N. Mex.; *D*, Pecos River near Puerto de Luna, N. Mex.; *E*, Pecos River near Artesia, N. Mex.; *F*, San Juan River near Archuleta, N. Mex.; and *G*, Animas River at Farmington, N. Mex.

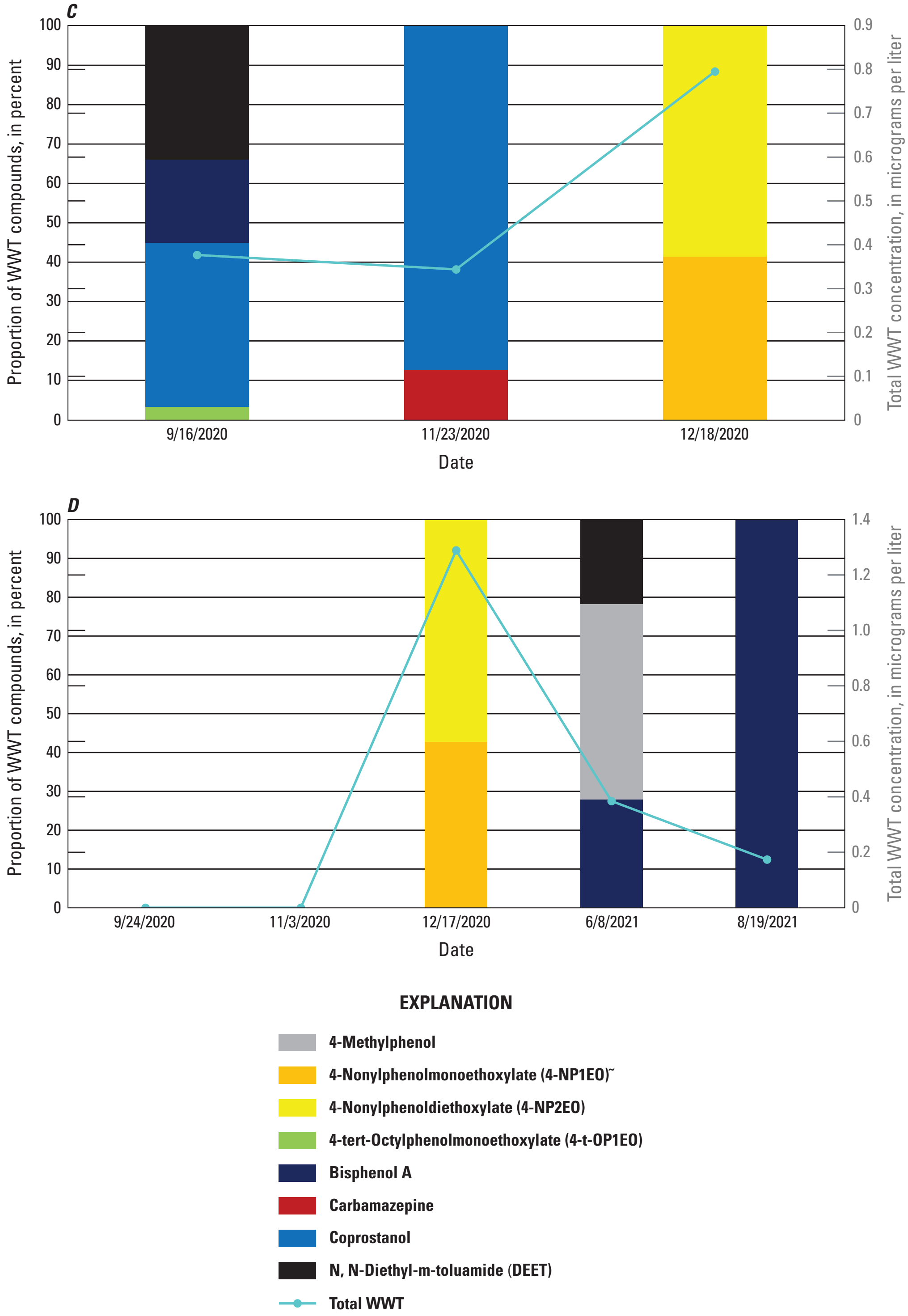


Figure 15.—Continued

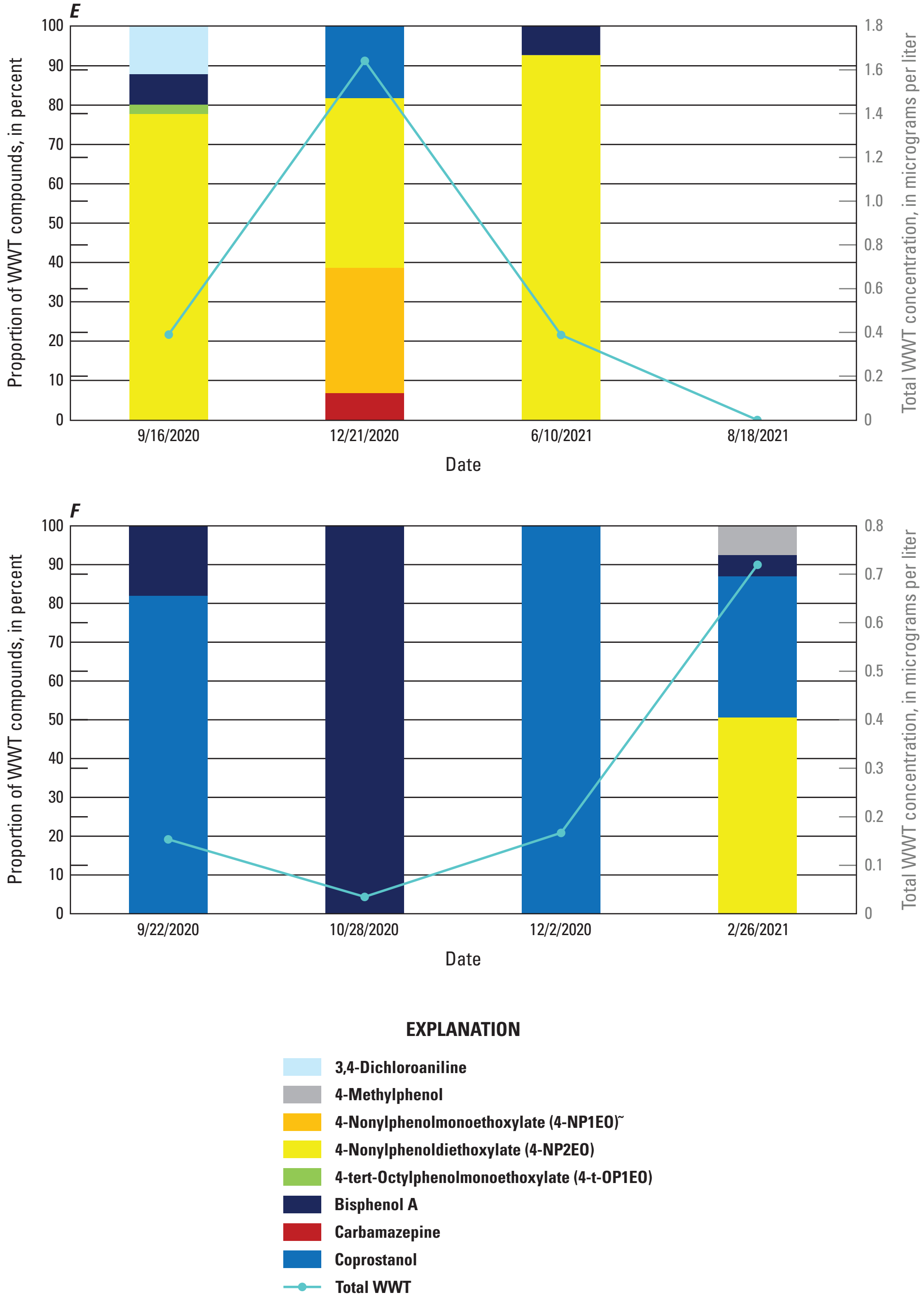


Figure 15.—Continued

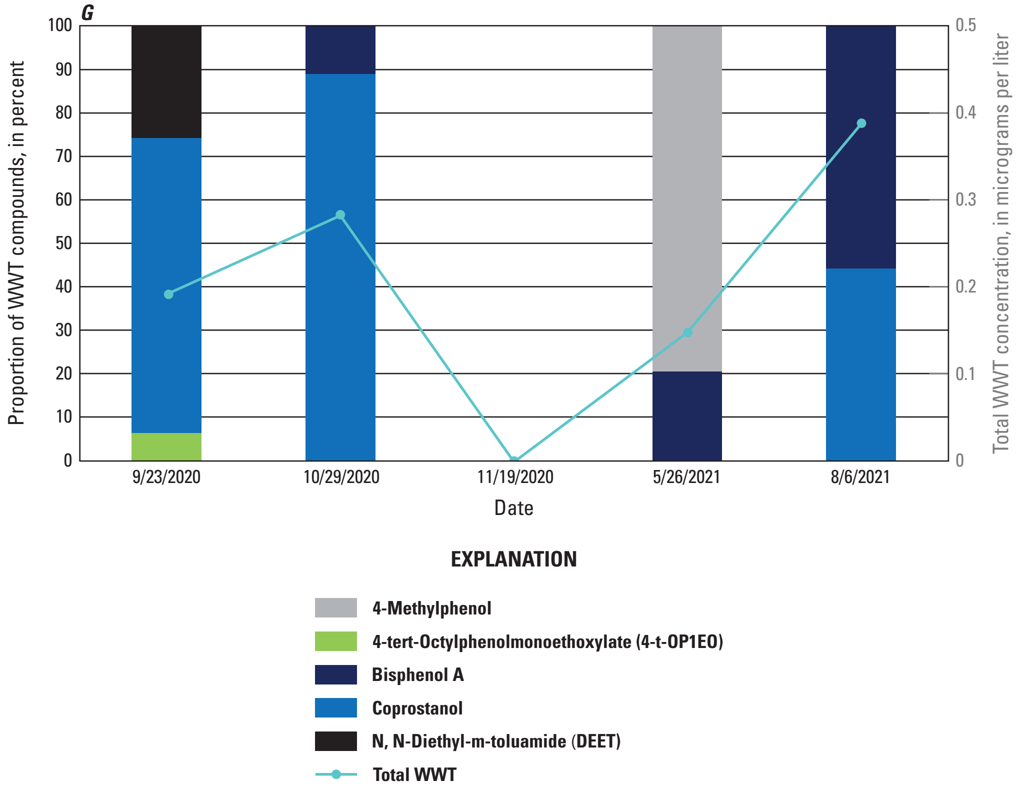


Figure 15.—Continued

Samples collected from Animas Farmington on certain dates plotted with the high conductivity waters (water group 1: sampling dates October 29, 2020, September 23, 2020, and August 6, 2021) and samples collected on other dates plotted much closer to the waters with relatively high trace-element and REE concentrations (water group 2: sampling dates November 19, 2020, and May 26, 2021). San Juan Archuleta differed from other study sites along the second principal component axis (fig. 16*A*).

REEs were normalized to the North American shale composite (Gromet and others, 1984; Piper and Bau, 2013) to understand anomalous values, and these ratios are plotted in figure 17. A Gd anomaly related to wastewater will tend toward greater peak height, in contrast to other nearby REEs. A positive Gd anomaly is observed in figure 17*H* for Animas Farmington on September 23, 2020, and October 29, 2020, whereas Gd enrichment is not observed for the later sampling dates of November 19, 2020, May 26, 2021, and August 6, 2021. This anomaly at Animas Farmington may suggest a wastewater signature because of the presence of three wastewater treatment facilities nearby. The drop in Gd enrichment after October 2020 could be due to lower frequency of MRI screenings during this time resulting either from medical services restrictions during the COVID-19 pandemic, changes in local hospital waste policies, WWTP upgrades, or dilution by additional sources of water to the river system. A positive Gd anomaly was also observed at Pecos Artesia only for the December 21, 2020, sample (fig. 17*F*), which corresponded with higher wastewater tracer detections, including carbamazepine, and may suggest a higher proportion of wastewater present at that site during that sampling event. Slight peaks in Gd may be present for the Rio Grande Alameda samples from November and December 2020 (fig. 17*D*) but were not observed at San Juan Archuleta or Rio Grande Buckman (fig. 17*B*, *G*).

Although an enrichment in Gd was observed at some of the other site locations, there was an enrichment in other REEs for the same samples, which could indicate that some Gd anomalies are from natural contributions rather than anthropogenic wastewater contributions. This natural geochemical contribution may explain the slight Gd enrichments observed in $Gd/Gd_{background}$ values for samples from Pecos Puerto de Luna on November 3, 2020 (fig. 17*E*), Pecos Artesia on September 16, 2021 (fig. 17*F*), and Rio Chama Abiquiu on November 17, 2020 (fig. 17*A*).

Table 21. Summary of wastewater tracer constituents and associated method identification, laboratory, and detection level information.

[NA, value not available; aka, also known as]

Analyte name	Constituent class	Chemical abstract service number	Method detection level (MDL)	Method detection level units	Possible chemical indicator of the following environmental source(s)
Boron	Trace element	7440-42-8	0.7	Micrograms per liter	Domestic wastewater
Gadolinium	Trace element	7440-54-2	0.0002	Micrograms per liter	Domestic wastewater
Carbon, dissolved organic	Organic matter characterization	7440-44-0	0.05–0.1	Milligrams per liter	Domestic wastewater, agricultural livestock
Acetylhexamethyltetrahydronaphthalene (AHTN); aka tonalide	Fragrance	21145-77-7	0.027	Micrograms per liter	Domestic wastewater
Atrazine	Herbicide	1912-24-9	0.027	Micrograms per liter	Agriculture crops
Atrazine desethyl	Herbicide degradate	6190-65-4	0.027	Micrograms per liter	Agriculture crops
Bisphenol A	Polycarbonate resins, antioxidant, flame retardant	80-05-7	0.027	Micrograms per liter	Domestic/industrial wastewater
2[3]-*tert*-Butylmethoxyphenol	Antioxidant	25013-16-5	0.05	Micrograms per liter	Domestic/industrial wastewater
4-*tert*-Butylphenol	Flame retardant, coating additive	98-54-4	0.027	Micrograms per liter	Domestic/industrial wastewater
Caffeine	Stimulant	58-08-2	0.027	Micrograms per liter	Domestic wastewater
Carbamazepine	Anticonvulsant	298-46-4	0.027	Micrograms per liter	Domestic wastewater
Cholesterol	Fecal indicator, animal/plant sterol	57-88-5	[1]0.25	Micrograms per liter	Domestic wastewater, agricultural livestock
Coprostanol; aka 5-beta-coprostanol	Carnivore fecal indicator	360-68-9	[1]0.10	Micrograms per liter	Domestic wastewater, agricultural livestock
Cotinine	Nicotine degradate	486-56-6	0.027	Micrograms per liter	Domestic wastewater
2,6-Di-*tert*-butyl-1,4-benzoquinone	Degradate of butylated hydroxytoluene antioxidant; also a plant treatment agent	719-22-2	0.027	Micrograms per liter	Domestic/industrial wastewater
2,6-Di-*tert*-butyl-4-methylphenol; aka butylated hydroxtoluene	Broad-use antioxidant used in food, animal feed, petroleum products, soaps, and more	128-37-0	0.027	Micrograms per liter	Domestic/industrial wastewater
2,6-Di-*tert*-butylphenol	Antioxidant	128-39-2	0.027	Micrograms per liter	Domestic/industrial wastewater
3,4-Dichloroaniline	Intermediate and degradate of dyes, antimicrobial triclocarban, and herbicides propanil, diuron, linuron	95-76-1	0.027	Micrograms per liter	Agriculture crops, domestic wastewater
1,2-Dichlorobenzene	Insecticide, versatile solvent, intermediate and degradate of agrochemicals	95-50-1	0.027	Micrograms per liter	Agriculture crops, domestic/industrial wastewater
1,3-Dichlorobenzene	Intermediate, but not commonly detected	541-73-1	0.027	Micrograms per liter	Agriculture crops, domestic/industrial wastewater

Table 21. Summary of wastewater tracer constituents and associated method identification, laboratory, and detection level information.—Continued

[NA, value not available; aka, also known as]

Analyte name	Constituent class	Chemical abstract service number	Method detection level (MDL)	Method detection level units	Possible chemical indicator of the following environmental source(s)
1,4-Dichlorobenzene	Disinfectant, deodorizer, pesticide, intermediate and degradate of dyes and polyphenylene sulfide polymer	106-46-7	0.027	Micrograms per liter	Agriculture crops, domestic/industrial wastewater
N,N-Diethyl-meta-toluamide (DEET)	Insect repellent	134-62-3	0.027	Micrograms per liter	Recreational activities, domestic wastewater
Diphenylhydramine chloride	Antihistamine	147-24-0	0.027	Micrograms per liter	Domestic wastewater
4-Ethylphenol	Fragrance and flavoring agent	123-07-9	0.027	Micrograms per liter	Domestic wastewater
Hexahydrohexamethylcyclopentabenzopyran (HHCB); aka galaxolide	Fragrance and flavoring agent	1222-05-5	0.027	Micrograms per liter	Domestic wastewater
5-Methyl-1H-benzotriazole	Antioxidant	136-85-6	[1]0.10	Micrograms per liter	Domestic/industrial wastewater
4-Methylphenol	Cosmetic, fragrance and flavoring agent	106-44-5	0.025	Micrograms per liter	Domestic wastewater
4-Nonylphenol	Precursor of antioxidants and detergents	104-40-5	0.25	Micrograms per liter	Domestic/industrial wastewater
4-Nonylphenolmonoethoxylate; aka NP1EO	Detergent, non-ionic surfactant	9016-45-9	0.25	Micrograms per liter	Domestic/industrial wastewater
4-Nonylphenoldiethoxylate, aka NP2EO	Detergent, non-ionic surfactant	9016-45-9	0.25	Micrograms per liter	Domestic/industrial wastewater
4-normal-Octylphenol	Precursor of detergents	1806-26-4	0.05	Micrograms per liter	Domestic/industrial wastewater
4-*tert*-Octylphenol	Precursor of detergents	140-66-9	0.05	Micrograms per liter	Domestic/industrial wastewater
4-*tert*-Octylphenolmonoethoxylate; aka OP1EO	Detergent, anionic surfactant	9036-19-5	0.01	Micrograms per liter	Domestic/industrial wastewater
4-*tert*-Octylphenoldiethoxylate; aka OP2EO	Detergent, anionic surfactant	2315-61-9	[1]0.08	Micrograms per liter	Domestic/industrial wastewater
4-*tert*-Octylphenoltriethoxylate; aka OP3EO	Detergent, anionic surfactant	4-t-OP3EO	0.05	Micrograms per liter	Domestic/industrial wastewater
4-*tert*-Octylphenoltetraethoxylate; aka OP4EO	Detergent, anionic surfactant	4-t-OP4EO	0.10	Micrograms per liter	Domestic/industrial wastewater
4-*tert*-Pentylphenol	Detergent degradate, precursor to phenolic resins	80-46-6	0.027	Micrograms per liter	Domestic/industrial wastewater
4-Propylphenol	Fragrance and flavoring agent	645-56-7	0.05	Micrograms per liter	Domestic/industrial wastewater
Triclosan	Disinfectant, antimicrobial	3380-34-5	0.027	Micrograms per liter	Domestic wastewater

[1] Raised reporting level.

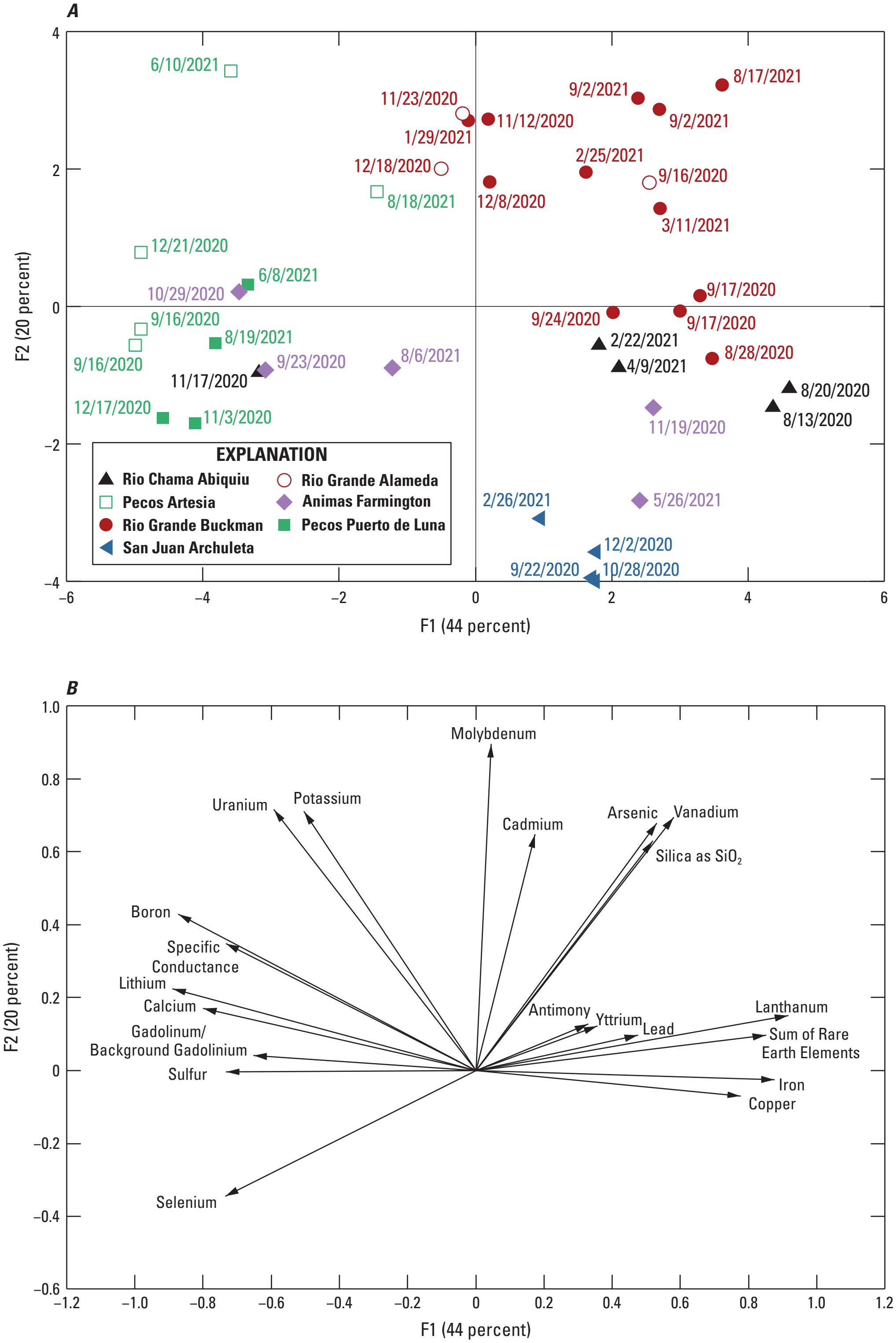
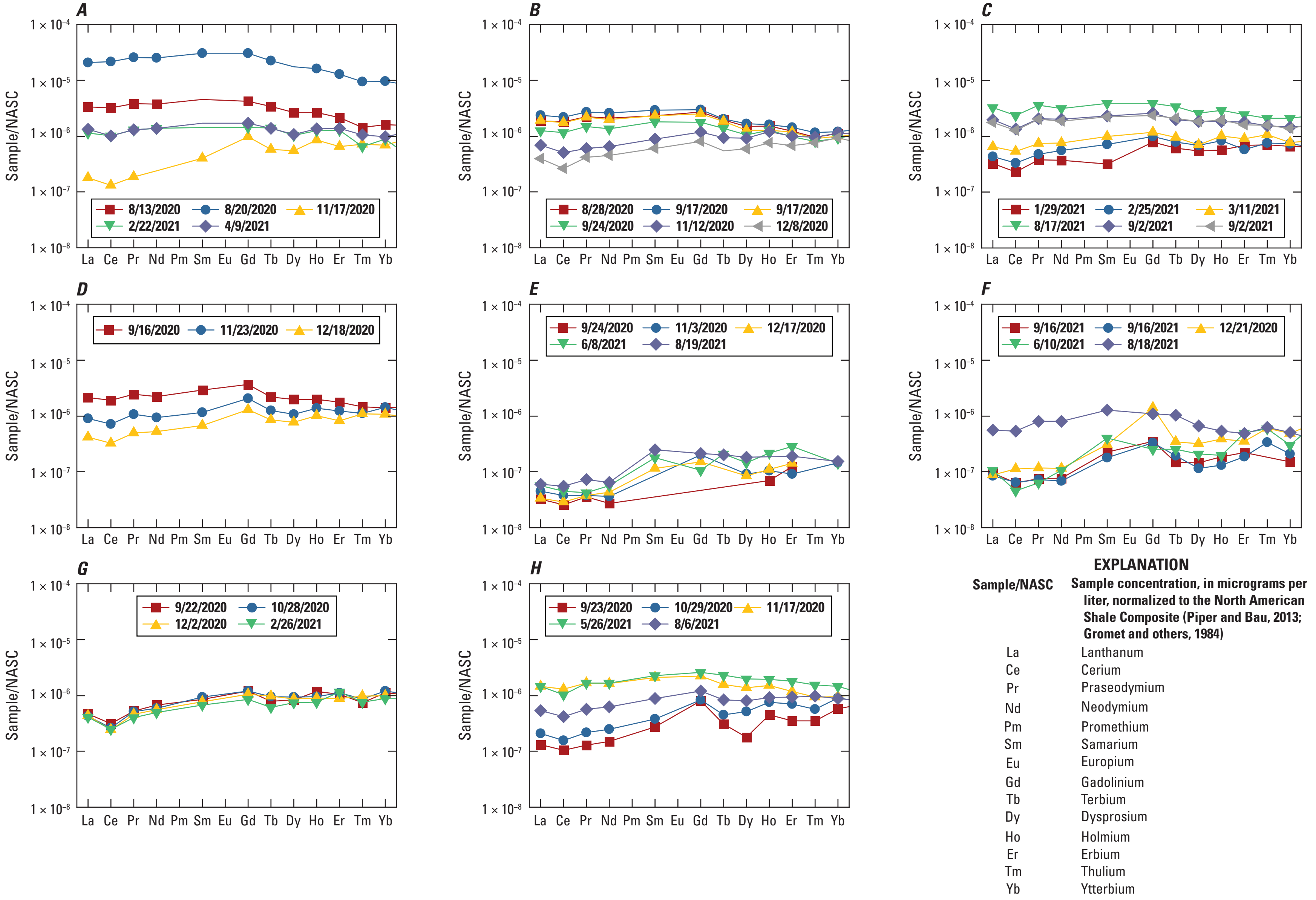


Figure 16. Principal components analysis of Spearman-ranked trace-element data. *A*, Surface-water samples plotted relative to their position on the principal component axes, where the different symbols are used for each location and the sampling date is next to the symbol, and *B*, plot of the magnitude and direction of chemical analytes that influence separation of surface-water samples along principal components.



EXPLANATION

Sample/NASC	**Sample concentration, in micrograms per liter, normalized to the North American Shale Composite (Piper and Bau, 2013; Gromet and others, 1984)**
La	Lanthanum
Ce	Cerium
Pr	Praseodymium
Nd	Neodymium
Pm	Promethium
Sm	Samarium
Eu	Europium
Gd	Gadolinium
Tb	Terbium
Dy	Dysprosium
Ho	Holmium
Er	Erbium
Tm	Thulium
Yb	Ytterbium

Figure 17. Observed rare earth element concentrations normalized to the North American shale composite (NASC) (Gromet and others, 1984; Piper and Bau, 2013) show gadolinium anomalies for surface-water samples from *A*, Rio Chama near Abiquiu Dam, New Mexico; *B*, Rio Grande above Buckman Diversion near White Rock, N. Mex. (2020 samples only); *C*, Rio Grande above Buckman Diversion near White Rock, N. Mex. (2021 samples only); *D*, Rio Grande at Alameda Bridge at Alameda, N. Mex.; *E*, Pecos River near Puerto de Luna, N. Mex.; *F*, Pecos River near Artesia, N. Mex.; *G*, San Juan River near Archuleta, N. Mex.; and *H*, Animas River at Farmington, N. Mex.

Multivariate Statistical Relations Between PFAS and Geochemical Indicators

Multivariate statistics can provide a helpful analysis of factors contributing to water evolution and to the occurrence of anthropogenic compounds. NMDS and cluster analyses were performed separately for groundwater and surface-water samples.

Groundwater

Multivariate analysis was conducted for 15 groundwater sites that had PFAS above the laboratory reporting level. Dissimilarity between samples was assessed using NMDS for tritium, DOC, and certain PFAS (PFBS, PFBA, 6:2FTS, PFHxA, PFOA, and PFPeA). Some sites had low-level detections of other PFAS (PFDA, PFHpA, PFHxS, PFNA, PFOS, and PFPeS) that were close to laboratory detection levels and did not show differentiation compared with censored values. The NMDS analysis of groundwater samples resulted in two convergent solutions with a stress of 0.065 (fig. 18). NMDS stress values ≤0.1 are considered fair, values ≤0.05 indicate good fit, and values ≥ 0.2 are deemed suspect, suggesting a fair to good fit for the groundwater samples (Buttigieg and Ramette, 2014). Separation between samples along the first NMDS axis (NMDS1 in fig. 18) was driven by differences in tritium, DOC, and nitrate. PFHxA, PFBS, and PFPeA show some similarity and are correlated with each other (fig. 19), whereas PFBA separates samples on the secondary NMDS axis (NMDS2 in fig. 18) and is significantly correlated (p value of 0.02) only with tritium. Two samples (48 and 82.1) had only 6:2FTS detections and plotted separately from the other samples. The sample from site 106 had a detection only of PFOA, along with elevated nitrate and low tritium and DOC. Two sites (18 and 44) were sampled more than once and show similarity between the samples compared with other sites. A cluster analysis was also run on the same analytes that were included in the NMDS, with the highest Calinski criterion of 11.2 at eight groups, indicating that there are eight distinct groups (as indicated by the colors of sample numbers on figure 20). The large number of distinct groups identified within a small sample set suggests that widely varying geochemical processes and sources of anthropogenic compounds contribute to the PFAS signature of each groundwater sample. Therefore, tritium, DOC, and nitrate alone may not be representative proxies for assessing PFAS on a statewide scale across New Mexico, although they could be relevant on a local scale.

PFAS Occurrence and Geochemical Indicators in Groundwater

The correlation of some PFAS with tritium suggests that the contribution of groundwater recharge occurring after 1952 is important to understand PFAS occurrence in the groundwater sampled for this study. Groundwater samples with detections of PFAS generally had tritium values in the mixed and modern category, ranging from 1.06 to 17.56 pCi/L, suggesting that these groundwater sites yielded samples containing a component of water that fell as precipitation after 1952. Groundwater recharge occurring during the modern period may be more likely to interact with and mobilize anthropogenic compounds present at the surface that become incorporated into the water as it moves through the subsurface, ultimately becoming part of the groundwater (Böhlke and Denver, 1995; Manning and others, 2005; McMahon, 2012). Five sites with detections of PFAS (sites 14, 18, 19, 48, and 106) had premodern values of tritium (fig. 21). One possible explanation for samples of premodern water having PFAS detections is that PFAS are present in a contribution from anthropogenic infrastructure, such as septic system or wastewater treatment plant effluent, where the water was originally derived from pumping of premodern groundwater; because the tritium is part of the water molecule, more tritium would not be acquired from contact with the modern atmosphere (Kuroda and others, 2014).

Tritium concentrations can help to explain differences in PFAS occurrence in groundwater from nearby wells. Two wells (43 and 44), located within 0.5 mi of each other and completed at similar depths in the High Plains aquifer, showed differences in tritium concentration (below the sample-specific critical levels of 0.2 and 2.38 pCi/L, respectively) and in corresponding groundwater age category. Site 44 was sampled three times and had some of the highest total PFAS concentrations observed during this study, ranging from 63.1 to 80.3 ng/L, whereas site 43 was sampled twice and had no PFAS detections. The tritium concentration at site 44 suggests a contribution of modern water is present that may be related to the PFAS detections.

Sites 124, 125, and 128 had PFAS detections in samples collected in April 2021 (samples ending with ".1"), but not in samples from October 2021 (samples ending with ".2") (table 16). Sites 124 and 125 had elevated specific conductance (2,670 and 961 µS/cm) and pH values (8.1 and 7.8) compared with nearby groundwater sites. Sites 112–127, excluding 124 and 125, had specific conductance ranging from 469 to 894 µS/cm. In contrast, site 128 had lower specific conductance (372 µS/cm).

For the April 2021 samples, the water types differed among all three sites (124, 125, 128) compared to the compositions of groundwater from other sites in that area (112–119, 123, 126, 127, 129–132) (fig. 8*A*). The October 2021 samples for sites 124, 125, and 128 were more similar to the general group of samples in that area, which have calcium-bicarbonate type waters.

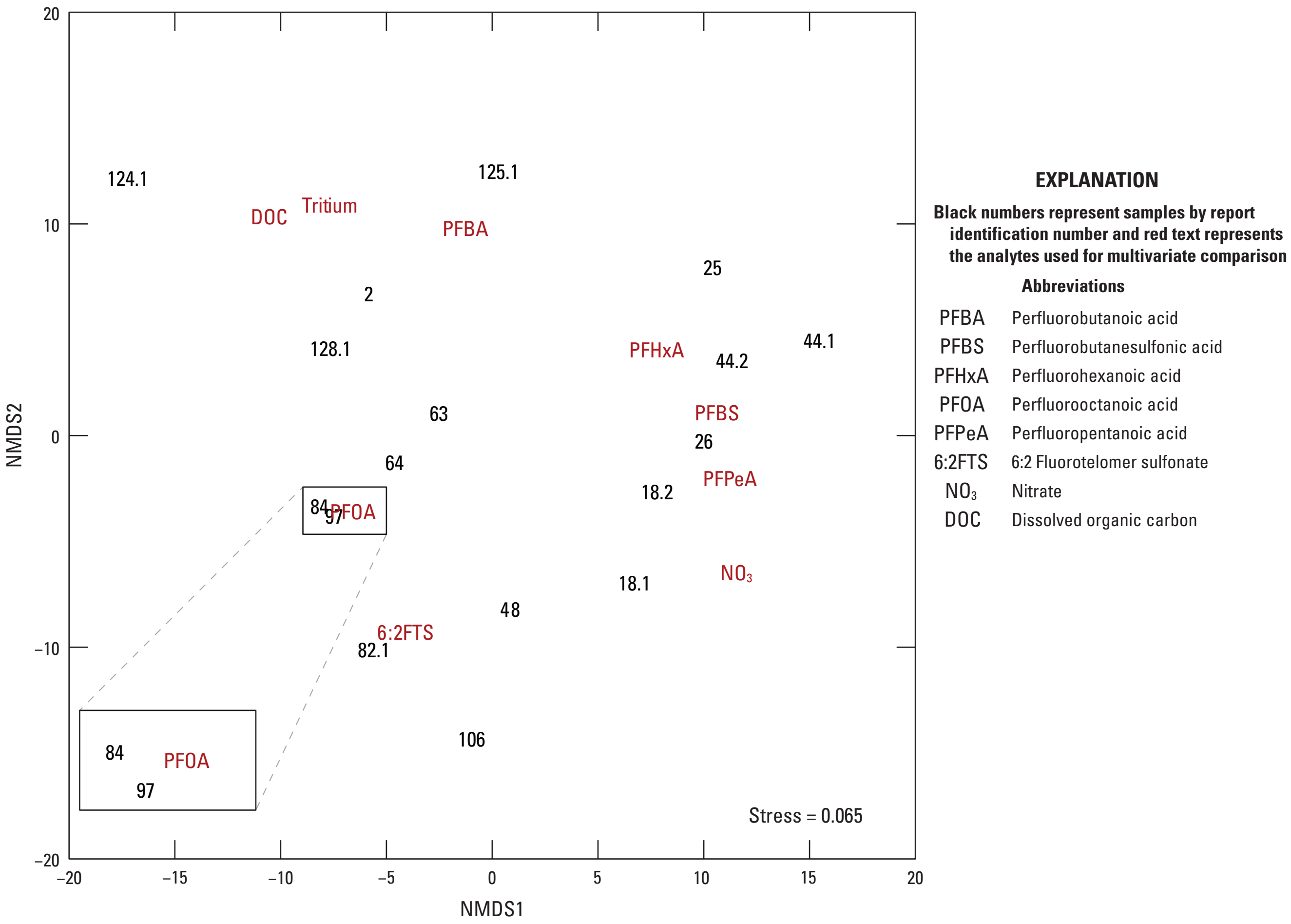


Figure 18. Nonmetric multidimensional scaling (NMDS) plot for groundwater samples with per- and polyfluoroalkyl substances detections. Dashed lines show closeup view of area with close data points.

Springs 124, 125, and 128 had an evaporative stable isotopic signature during the April 2021 sampling event (fig. 10). When the springs were resampled in October 2021 and flow was higher, they did not have any PFAS detected and had stable isotopic signatures similar to those of other springs and wells in the area during the April sampling event (sites 112–128). The samples with PFAS detections may indicate concentration in evaporated water that is localized and not representative of other groundwater in the area.

Springs 124, 125, and 128 had PFAS detected in samples collected in April 2021 and had higher tritium concentrations (11.94–17.56 pCi/L) than nearby springs and wells (sites 112–128; 4.2–9.34 pCi/L). The samples with PFAS detections and elevated tritium may represent evaporated water or other seasonal contributions of modern water that are localized and not representative of other groundwater in the area.

Two other sites located near each other (140 and 141) had a large difference in tritium, as well as a difference in stable isotopes, suggesting that the source of water to each site was different. Site 140 is located closer to the Rio Grande and had a higher TDS value (675 mg/L), a more enriched and evaporated stable isotopic signature (−77.6 and −9.42 per mil for δ^2H and δ^{18}O, respectively), a tritium concentration of 11.5 pCi/L, and a higher ^{14}C concentration of 94.7 pmc; site 141 had a lower TDS value (473 mg/L), lighter stable isotopes (−89.1 and −11.4 per mil for δ^2H and δ^{18}O, respectively), a tritium concentration below the sample-specific critical level (analogous to the laboratory reporting level) of 0.06 pCi/L, and a lower ^{14}C concentration of 56.1 pmc. Site 141 had results more similar to other groundwater sampled farther south in Doña Ana County at sites 144, 145, and 146 (which all had a higher proportion of sodium). There was a low-level PFOS detection at site 140, and the presence of modern evaporated water may suggest that the component of younger water (possibly recharge from the Rio Grande) is susceptible to anthropogenic compounds.

Surface Water

Multivariate analysis was conducted for 61 surface-water samples that had PFAS concentrations above the laboratory reporting level. Other analytes associated with PFAS samples were not collected for all surface-water samples, so they

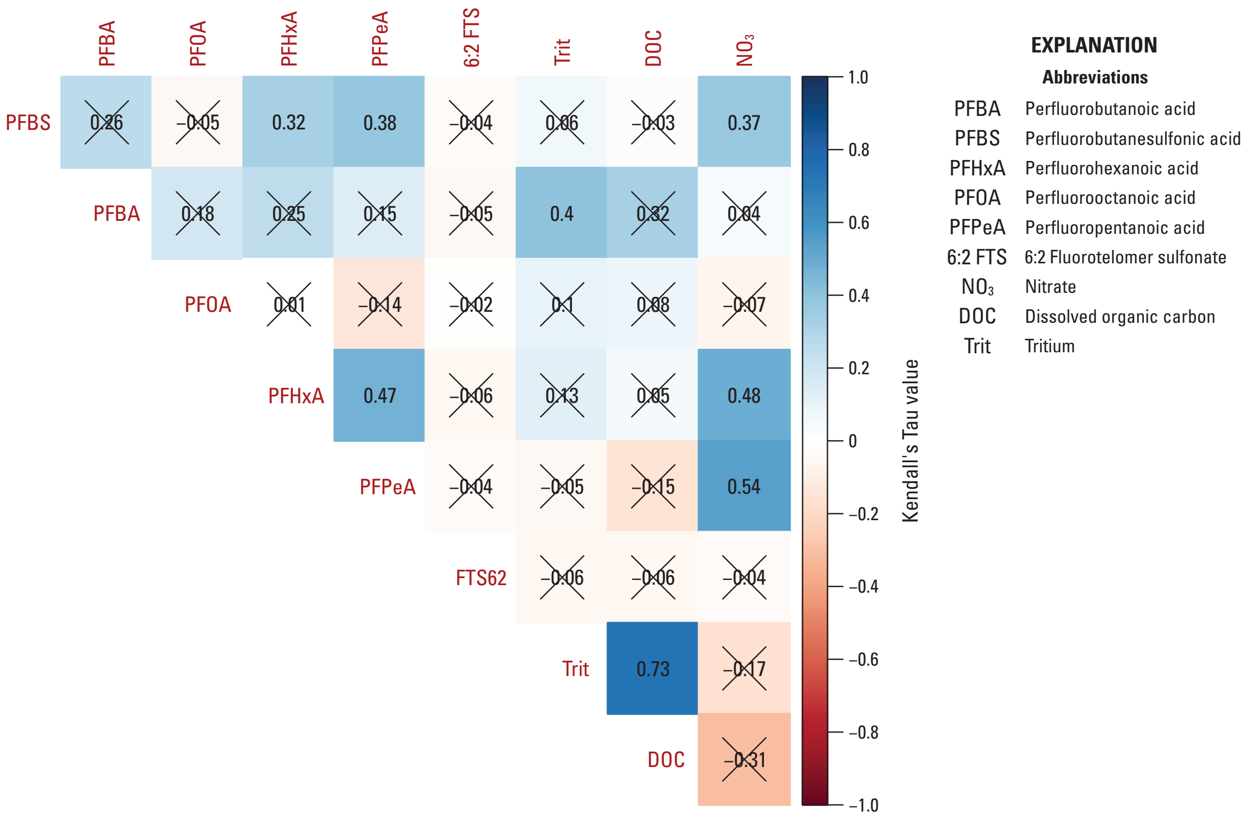


Figure 19. Correlation matrix for groundwater samples with per- and polyfluoroalkyl substances detections including the Kendall's tau value for elemental pairs, where values with an X are not statistically significant with p greater than 0.05.

were not added to the multivariate analysis presented here. Dissimilarity between samples was assessed using NMDS for certain PFAS (PFBS, PFBA, 6:2FTS, PFHxA, PFOA, PFOS, and PFPeA). Some sites had low-level detections of other PFAS (PFDA, PFHpA, PFHxS, PFNA, PFOSA, and PFPeS) that were close to laboratory reporting levels and did not show differentiation compared with censored values. The NMDS analysis of surface-water samples resulted in two convergent solutions with a stress of 0.10 (fig. 22), suggesting a fair fit (Buttigieg and Ramette, 2014). Separation between samples along the first NMDS axis (NMDS1 in fig. 22) was driven by differences between PFHxA, PFOA, PFOS, PFBA, and PFPeA compared with 6:2 FTS (which is not correlated with the other PFAS) (figs. 22 and 23), whereas PFBS separates samples on the first and secondary NMDS axes and is not correlated with other PFAS.

A cluster analysis was also run on the same analytes that were included in the NMDS, with the Calinski criterion indicating there are two distinct groups. The cluster analysis included a large number of samples, and the visual representation of these data was too crowded to display in a figure, so the results are discussed in this section without a figure to reference. The conclusion that PFAS results form two distinct groups in surface-water samples across the State suggests that there may be similar PFAS sources contributing to each distinct group of samples. One group includes samples with multiple detections of different PFAS (Rio Grande Valle de Oro, Rio Puerco Bernardo, Rio Grande Floodway and Rio Grande El Paso, some samples from Pecos Artesia, and some samples from Animas Farmington), and the other group includes samples with low-level PFAS below the laboratory reporting level or no detections of PFAS (all samples from Canadian Sanchez, Canadian Conchas, Canadian Logan, Rio Chama Abiquiu, Rio Grande Buckman, Rio Grande Alameda; samples from December 2020 and February and March 2021 at Rio Grande Valle de Oro, Pecos Puerto de Luna; some samples from October 2020 and June and August 2021 at Pecos Artesia, Pecos Red Bluff, San Juan Archuleta; and some samples from Animas Farmington, San Juan Fruitland, and Gila).

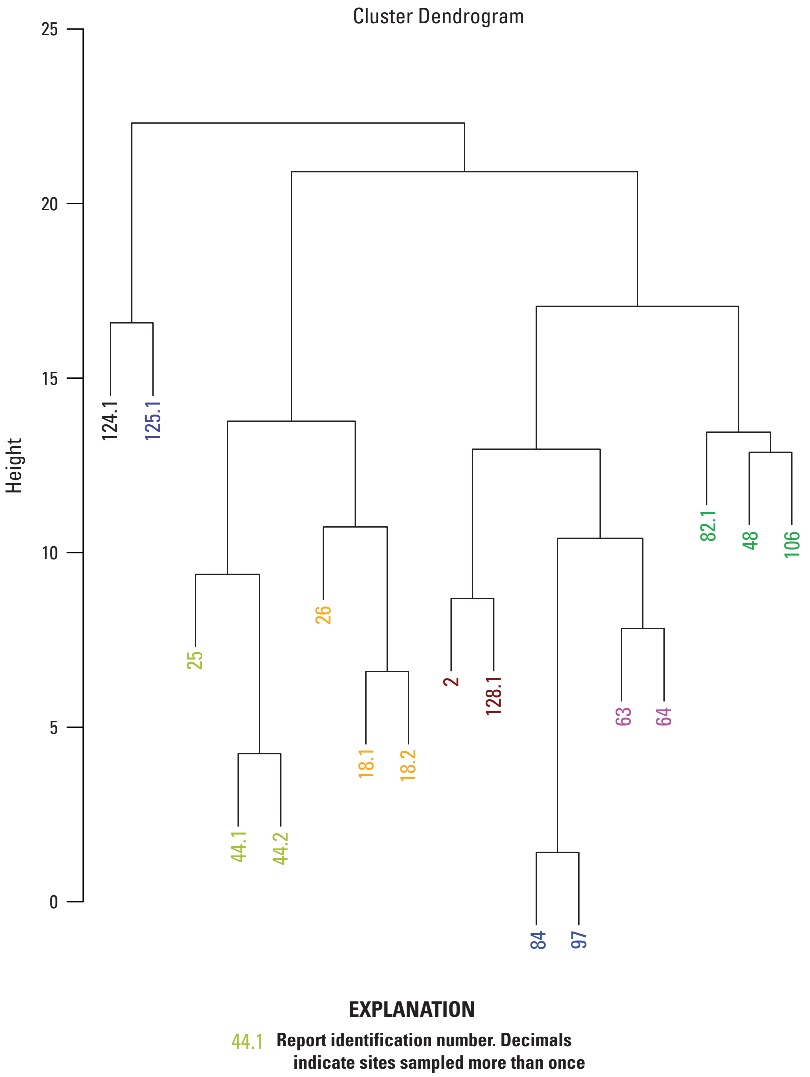


Figure 20. Cluster analysis for groundwater samples with per- and polyfluoroalkyl substances detections where colors distinguish different statistical groupings of the samples.

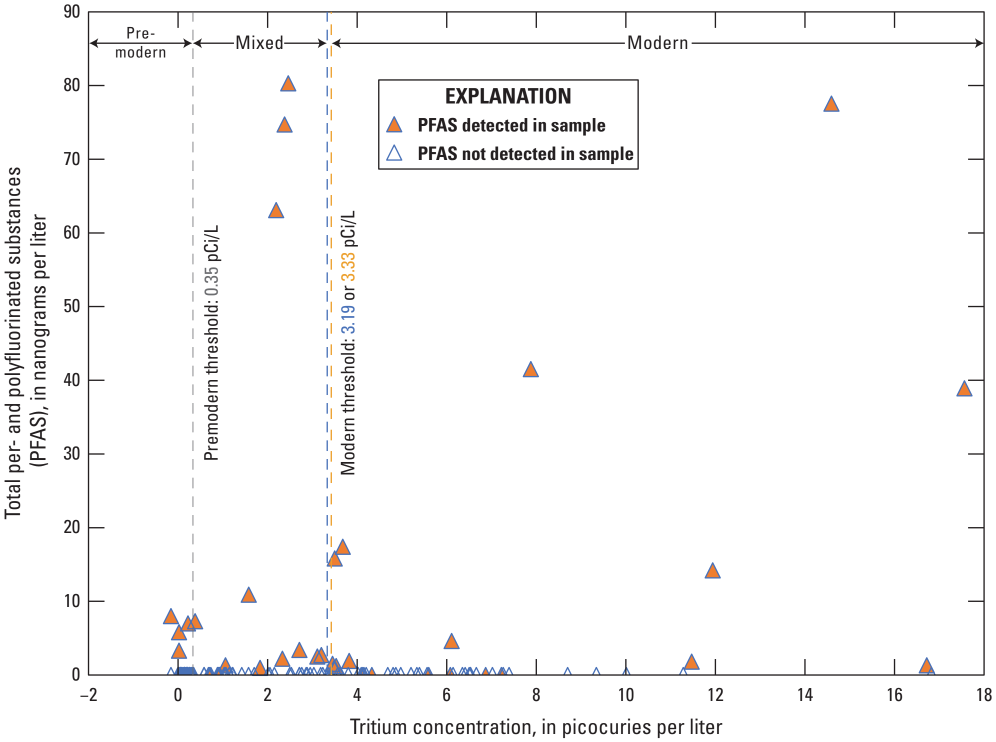
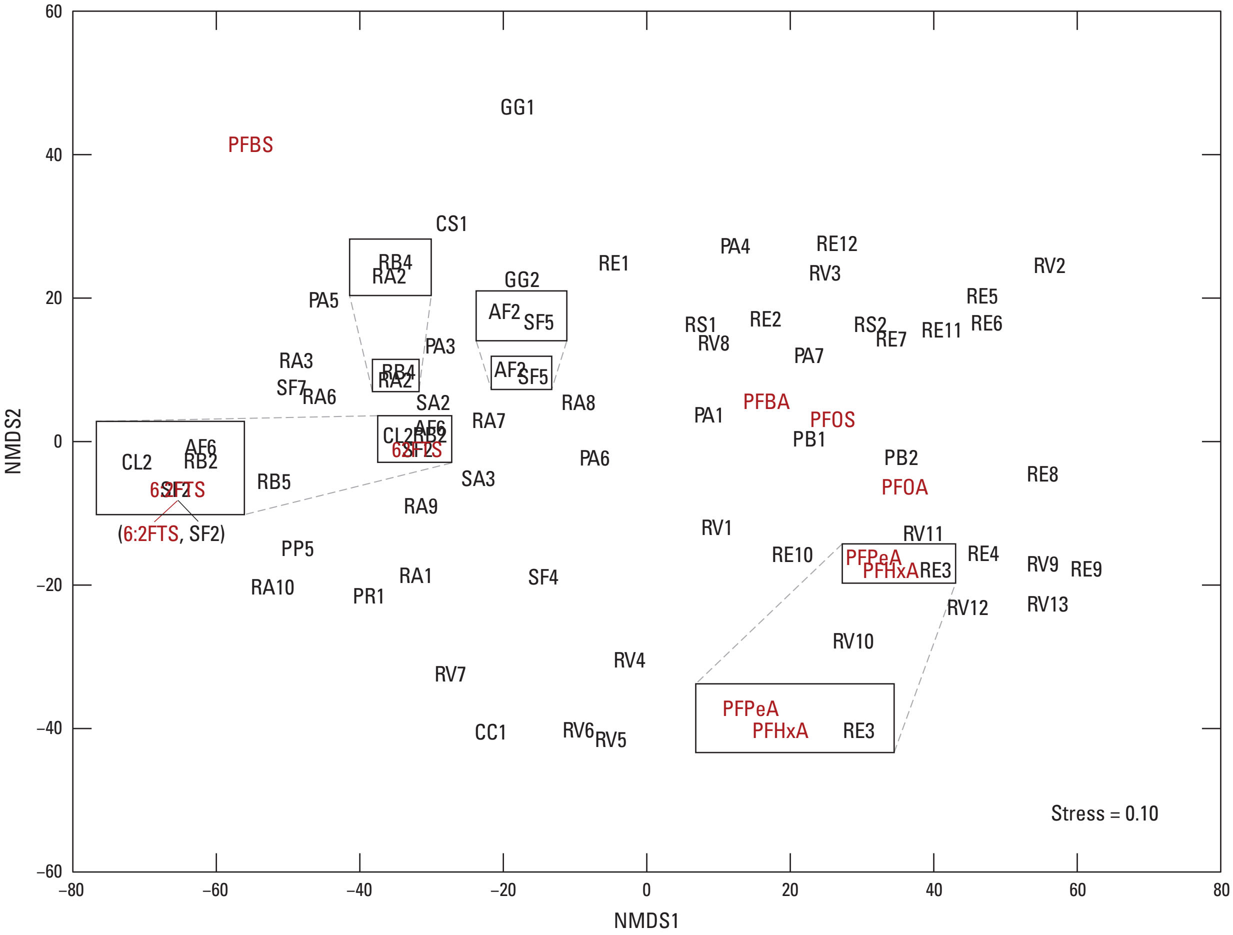


Figure 21. Tritium versus total per- and polyfluoroalkyl substances (PFAS) concentration.



EXPLANATION

Black numbers represent samples by report identification number and red text represents the analytes used for multivariate comparison

PR	**Pecos River at Red Bluff**	AF	**Animas River at Farmington**
RA	**Rio Grande at Alameda Bridge at Alameda**	CA	**Rio Chama below Abiquiu Dam**
RB	**Rio Grande above Buckman Diversion**	CC	**Canadian River below Conchas Dam**
RE	**Rio Grande at El Paso**	CL	**Canadian River at Logan**
RS	**Rio Grande Floodway at San Marcial**	CS	**Canadian River near Sanchez**
RV	**Rio Grande at Valle de Oro**	GG	**Gila River near Gila**
SA	**San Juan River near Archuleta**	PA	**Pecos River near Artesia**
SF	**San Juan River near Fruitland**	PP	**Pecos River near Puerto de Luna**

Figure 22. Nonmetric multidimensional scaling (NMDS) plot for surface-water samples with per- and polyfluoroalkyl substances detections.

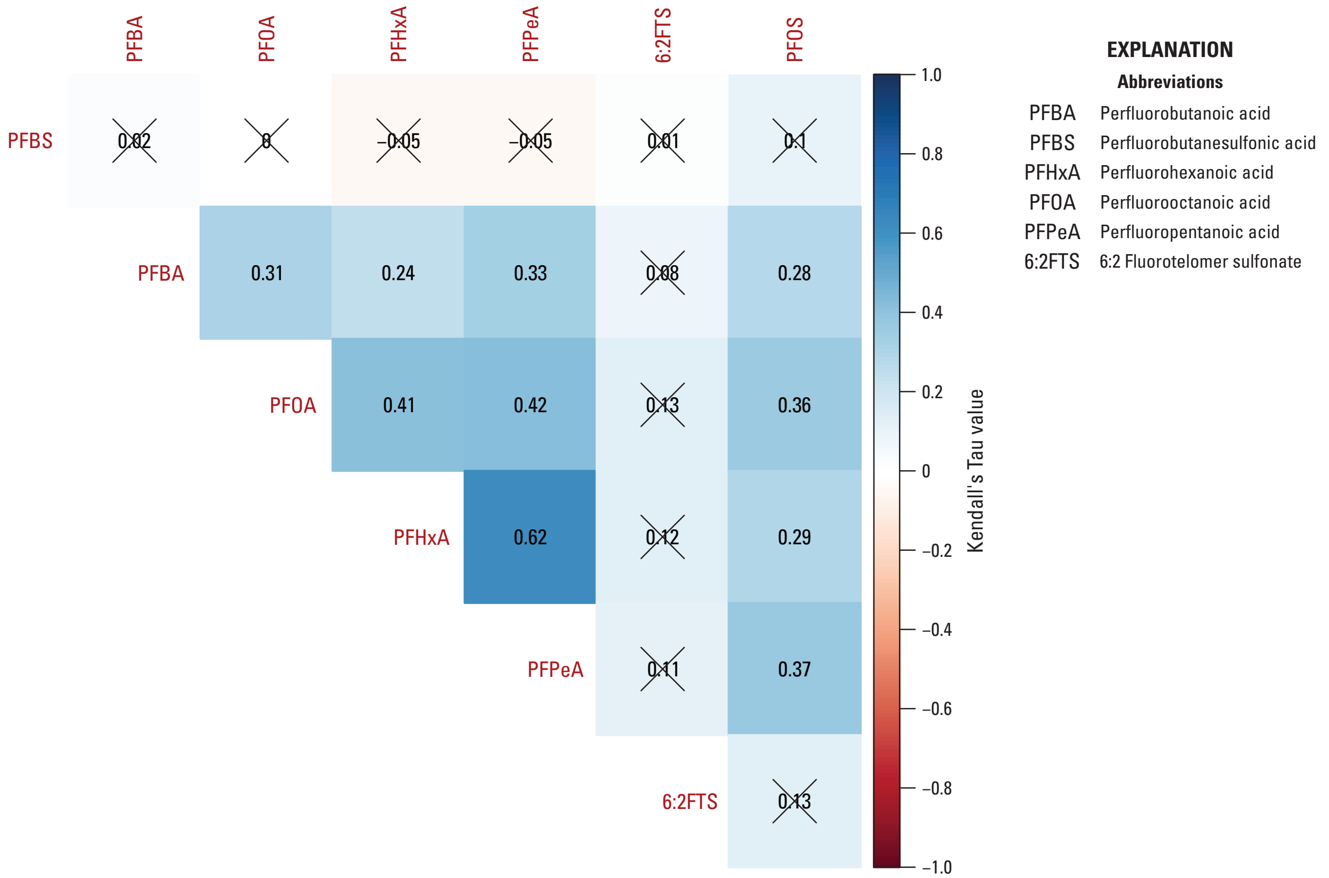


Figure 23. Correlation matrix for surface-water samples with per and polyfluoroalkyl substances detections including the Kendall's tau value for elemental pairs, where values with an X are not statistically significant with p greater than 0.05.

Limitations of a Statewide Assessment

The statewide scale of this study was designed to locate surface waters and groundwater with occurrence of PFAS to inform subsequent investigations into potential sources of these PFAS and allow for more focused sampling in areas where PFAS are present in drinking water. The existing study design made it difficult to perform statistically rigorous multivariate analyses or create correlational plots to definitively characterize geochemical characteristics of the sampled surface waters in relation to PFAS occurrence at this time, and particularly to characterize any relations between detections of wastewater tracers and PFAS. Wastewater tracers and geogenic/anthropogenic trace and REE concentrations could be used to better characterize sources of discharge into surface waters and to improve correlation analysis by (1) collecting PFAS, wastewater tracer, and trace and REE samples consistently from individual sites during single sampling events, and across multiple sites during similar time periods; (2) timing seasonal sampling events systematically to better capture low-flow and high-flow hydrologic events; and (3) choosing site locations that are above and below nearby urban development or facilities with potential PFAS use.

Summary

Per- and polyfluoroalkyl substances (PFAS) have previously been detected in public and private drinking-water wells, springs, and surface waters in New Mexico; however, the presence and distribution of PFAS in water resources across the State has not been well characterized. The U.S. Geological Survey, in cooperation with the New Mexico Environment Department, began collecting water-quality samples from groundwater and surface-water sites throughout New Mexico in August 2020. Sample locations were selected to cover a large spatial area, including urban areas and rural areas. Groundwater wells, springs, and surface-water sites (at established streamgaging locations) were sampled from August 2020 through October 2021.

Groundwater samples were collected from unconfined water-table aquifers at 117 groundwater well locations and 24 springs, and surface-water samples were collected from 6 surface-water diversions and 18 streamgaging locations, which were primarily sampled during stable flows and not after storm events. All samples were analyzed for PFAS and field parameters. Groundwater samples also were analyzed for an extensive geochemical suite (major ions, trace elements, nutrients, dissolved organic carbon [DOC], stable isotopes of oxygen and hydrogen, tritium, and carbon-14, and selected surface-water samples were analyzed for major ions, trace elements, DOC, and wastewater tracers. Blanks and replicates were collected to assess bias and variability in the results for PFAS, wastewater tracers, and geochemical compounds (including major ions, trace elements, nutrients, and DOC).

The majority of the groundwater samples from this study did not have any detections of PFAS. (Concentrations were reported by the laboratory as being below the laboratory detection level.) Over the course of the study, 22 sites were sampled more than once, and 3 sites were sampled as many as three times. At 30 sites, PFAS was detected during one or more sampling events. Total PFAS concentrations ranged from 0.91 nanograms per liter (ng/L) at site 136 to 80.3 ng/L at site 44 (second sampling). There were no exceedances of the 2016 U.S. Environmental Protection Agency health advisory of 70 ng/L for perfluorooctanoic acid (PFOA) plus perfluorooctane sulfonic acid (PFOS). The most frequently detected PFAS at groundwater sites were perfluorobutanesulfonic acid (PFBS; 11 sites), perfluoropentanoic acid (PFPeA; 10 sites), and perfluorohexanoic acid (PFHxA; 9 sites). The High Plains aquifer had the most detections, totaling 13 sites. Excluding the springs, the PFAS signature did not change substantially between initial sampling and resampling at each site.

PFAS detections were quite variable within and between surface-water systems. Some sites were located in undeveloped areas that were expected to represent reference sites with low to no PFAS detections, but some of those sites had intermittent PFAS detections. Other sites, particularly those located downstream from urban areas, had numerous PFAS detections. PFPeA was the most frequently detected PFAS across all sites and events (57 instances, ranging from 1.0 to 29 ng/L), and PFBS was the second most frequently detected PFAS (53 instances, ranging from 1.0 to 93 ng/L). Total PFAS concentrations ranged from 1.0 to 155.4 ng/L at Rio Grande Valle de Oro, which had the greatest single concentration of an individual PFAS with 93 ng/L of PFBS.

Statistical analysis of selected analytes from the groundwater results indicated that some PFAS were associated with each other (PFHxA, PFBS, and PFPeA), suggesting similar sources and that some PFAS compounds were also correlated with tritium, DOC, and nitrate, which indicated that the presence of anthropogenic compounds could indicate a likely presence of PFAS. However, a cluster analysis identified several groups, and suggested that varying geochemical processes and sources of anthropogenic compounds contribute to the PFAS signature of each individual groundwater sample. Therefore, tritium, DOC, and nitrate alone may not be representative proxies for assessing PFAS on a statewide scale across New Mexico, although they could be relevant on a local scale. In surface-water samples, PFHxA, PFOA, PFOS, perfluorobutanoic acid (PFBA), and PFPeA were correlated with each other, suggesting similar sources contribute these PFAS compounds to surface-water sites in this study.

Results of this study have helped to establish baseline PFAS occurrence in the water resources of New Mexico, provide geochemical context for groundwater and surface-water evolution, and elucidate knowledge gaps that could help refine sampling efforts in areas where PFAS are known to be present in the environment.

References Cited

Ahrens, L., Felizeter, S., Sturm, R., Xie, Z., and Ebinghaus, R., 2009, Polyfluorinated compounds in waste water treatment plant effluents and surface waters along the River Elbe, Germany: Marine Pollution Bulletin, v. 58, no. 9, p. 1326–1333, accessed March 29, 2022, at https://doi.org/10.1016/j.marpolbul.2009.04.028.

Albuquerque Bernalillo County Water Utility Authority, 2021, Albuquerque's drinking water system: Albuquerque Bernalillo County Water Utility Authority web page, accessed February 4, 2022, at https://www.abcwua.org/education-education-el_wsd_2/.

Albuquerque Bernalillo County Water Utility Authority, 2022, San Juan-Chama Project: Albuquerque Bernalillo County Water Utility Authority web page, accessed September 28, 2022, at https://www.abcwua.org/your-drinking-water-san-juan-chama-project/.

Anderholm, S.K., 1987, Hydrogeology of the Socorro and La Jencia Basins, Socorro County, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 84–4342, 62 p., accessed April 8, 2022, at https://pubs.usgs.gov/wri/1984/4342/report.pdf.

Barber, L.B., Brown, G.K., and Zaugg, S.D., 2000, Potential endocrine disrupting organic chemicals in treated municipal wastewater and river water, *in* Keith, L.H., Jones-Lepp, T.L., and Needham, L.L., eds., Analysis of environmental endocrine disruptors: Washington D.C., American Chemical Society Symposium Series 747, p. 97–123.

Bartolino, J.R., and Cole, J.C., 2002, Ground-water resources of the Middle Rio Grande Basin, New Mexico: U.S. Geological Survey Circular 1222, 132 p., accessed November 28, 2021, at https://doi.org/10.3133/cir1222.

Bau, M., and Dulski, P., 1996, Anthropogenic origin of positive gadolinium anomalies in river waters: Earth and Planetary Science Letters, v. 143, nos. 1–4, p. 245–255.

Bau, M., Knappe, A., and Dulski, P., 2006, Anthropogenic gadolinium as a micropollutant in river waters in Pennsylvania and in Lake Erie, northeastern United States: Geochemistry, v. 66, no. 2, p. 143–152.

Beisner, K.R., and Jones, C.J.R., 2020, Geochemical assessment of groundwater in the Big Chino subbasin, Arizona, 2011–18: U.S. Geological Survey Scientific Investigations Report 2020–5094, 49 p., accessed September 29, 2022, at https://doi.org/10.3133/sir20205094.

Bexfield, L.M., Thiros, S.A., Anning, D.W., Huntington, J.M., and McKinney, T.S., 2011, Effects of natural and human factors on groundwater quality of basin-fill aquifers in the southwestern United States—Conceptual models for selected contaminants: U.S. Geological Survey Scientific Investigations Report 2011–5020, 90 p., accessed September 29, 2022, at https://pubs.usgs.gov/sir/2011/5020/.

Böhlke, J.K., and Denver, J.M., 1995, Combined use of groundwater dating, chemical, and isotopic analyses to resolve the history and fate of nitrate contamination in two agricultural watersheds, Atlantic Coastal Plain, Maryland: Water Resources Research, v. 31, no. 9, p. 2319–2339, accessed April 28, 2022, at https://doi.org/10.1029/95WR01584.

Boone, J.S., Vigo, C., Boone, T., Byrne, C., Ferrario, J., Benson, R., Donohue, J., Simmons, J.E., Kolpin, D.W., Furlong, E.T., and Glassmeyer, S.T., 2019, Per- and polyfluoroalkyl substances in source and treated drinking waters of the United States: Science of the Total Environment, v. 653, p. 359–369, accessed August 4, 2021, at https://doi.org/10.1016/j.scitotenv.2018.10.245.

Buckman Direct Diversion, 2015, How the BDD works: Buckman Direct Diversion Project web page, accessed December 10, 2021, at https://bddproject.org/about-the-bdd/how-the-bdd-works/.

Bureau of Reclamation, 2021, Pecos River Basin—New Mexico: Bureau of Reclamation web page, accessed February 8, 2022, at https://www.usbr.gov/watersmart/bsp/docs/finalreport/Pecos/PRNMB-final-9-20-2021.pdf.

Busch, J., Ahrens, L., Sturm, R., and Ebinghaus, R., 2010, Polyfluoroalkyl compounds in landfill leachates: Environmental Pollution, v. 158, no. 5, p. 1467–1471, accessed March 29, 2022, at https://doi.org/10.1016/j.envpol.2009.12.031.

Buttigieg, P.L., and Ramette, A., 2014, A guide to statistical analysis in microbial ecology—A community-focused, living review of multivariate data analyses: FEMS Microbiology Ecology, v. 90, p. 543–550.

City of Albuquerque Parks and Recreation Department Open Space Division, 2014, Resource Management Plan for Tijeras Arroyo Biological Zone: City of Albuquerque web page, accessed December 13, 2021, at https://www.cabq.gov/parksandrecreation/documents/r-82-resource-mgmt-plan-for-tijeras-arroyo-final.pdf.

Clarke, K.R., Gorley, R.N., Somerfield, P.J., and Warwick, R.M., 2014, Ordination of samples by multi-dimensional scaling (MDS), chap. 5 *of* Change in marine communities—An approach to statistical analysis and interpretation (3d ed.): Devon, U.K., PRIMER-E Ltd., [variously paged].

Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, no. 3465, p. 1702–1703, accessed September 24, 2022, at https://doi.org/10.1126/science.133.3465.1702.

Craigg, S.D., 2001, Geologic framework of the San Juan structural basin of New Mexico, Colorado, Arizona, and Utah, with emphasis on Triassic through Tertiary rocks: U.S. Geological Survey Professional Paper 1420, 70 p.

Crone, B.C., Speth, T.F., Wahman, D.G., Smith, S.J., Abulikemu, G., Kleiner, E.J., and Pressman, J.G., 2019, Occurrence of per-and polyfluoroalkyl substances (PFAS) in source water and their treatment in drinking water: Critical Reviews in Environmental Science and Technology, v. 49, no. 24, p. 2359–2396, accessed April 14, 2022, at https://doi.org/10.1080/10643389.2019.1614848.

Dam, W., 1995, Geochemistry of ground water in the Gallup, Dakota, and Morrison aquifers, San Juan Basin, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 94–4253, 76 p.

Dewitz, J., and U.S. Geological Survey, 2021, National Land Cover Database (NLCD) 2019 products (ver. 2.0, June 2021): U.S. Geological Survey data release, accessed November 8, 2021, at https://doi.org/10.5066/P9KZCM54.

Esri, 2023, ArcGIS Pro 3.1.1: Redlands, Calif., Environmental Systems Research Institute software release, accessed February 1, 2023, at https://community.esri.com/t5/arcgis-pro-documents/arcgis-pro-3-1-patch-1-is-now-available/ta-p/1276363.

Fishman, M.J., ed., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Open File Report 93–125, 217 p., accessed September 22, 2022, at https://doi.org/10.3133/ofr93125.

Fishman, M.J., and Friedman, L.C., 1989, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p., accessed September 22, 2022, at https://doi.org/10.3133/twri05A1.

Flickinger, A.K., and Shephard, Z.M., 2022, Water-quality trends in surface waters of the Jemez River and Middle Rio Grande Basin from Cochiti to Albuquerque, New Mexico, 2004–19: U.S. Geological Survey Scientific Investigations Report 2022–5062, 33 p., accessed September 29, 2022, at https://doi.org/10.3133/sir20225062.

Furlong, E.T., Werner, S.L., Anderson, B.D., and Cahill, J.D., 2008, Determination of human-health pharmaceuticals in filtered water by chemically modified styrene-divinylbenzene resin-based solid-phase extraction and high-performance liquid chromatography/mass spectrometry: U.S. Geological Survey Techniques and Methods, book 5, chap. B5, 56 p.

Garbarino, J.R., Kanagy, L.K., and Cree, M.E., 2006, Determination of elements in natural-water, biota, sediment, and soil samples using collision/reaction cell inductively coupled plasma–mass spectrometry: U.S. Geological Survey Techniques and Methods, book 5, chap. B1, 88 p., accessed September 22, 2022, at https://pubs.usgs.gov/tm/2006/tm5b1/.

Garbarino, J.R., and Taylor, H.E., 1979, An inductively coupled plasma-atomic emission spectrometric method for routine water quality testing: Applied Spectroscopy, v. 33, p. 220–226.

Garbarino, J.R., and Taylor, H.E., 1996, Inductively coupled plasma-mass spectrometric method for the determination of dissolved trace elements in natural water: U.S. Geological Survey Open-File Report 94–358, 49 p.

Glüge, J., Scheringer, M., Cousins, I.T., DeWitt, J.C., Goldenman, G., Herzke, D., Lohmann, R., Ng, C.A., Trier, X., and Wang, Z., 2020, An overview of the uses of per- and polyfluoroalkyl substances (PFAS): Environmental Science, Processes & Impacts, v. 22, p. 2345–2373, accessed March 29, 2022, at https://doi.org/10.1039/D0EM00291G.

Gromet, L.P., Haskin, L.A., Korotev, R.L., and Dymek, R.F., 1984, The “North American shale composite”—Its compilation, major and trace element characteristics: Geochimica et Cosmochimica Acta, v. 48, no. 12, p. 2469–2482, accessed July 13, 2022, at https://doi.org/10.1016/0016-7037(84)90298-9.

Han, L.-F., and Plummer, L.N., 2013, Revision of Fontes & Garnier’s model for the initial ^{14}C content of dissolved inorganic carbon used in groundwater dating: Chemical Geology, v. 351, p. 105–114, accessed November 16, 2021, at https://doi.org/10.1016/j.chemgeo.2013.05.011.

Han, L.-F., and Plummer, L.N., 2016, A review of single sample-based models and other approaches for radiocarbon dating of dissolved inorganic carbon in groundwater: Earth-Science Reviews, v. 152, p. 119–142, accessed November 16, 2021, at https://doi.org/10.1016/j.earscirev.2015.11.004.

Han, L.-F., Plummer, L.N., and Aggarwal, P., 2012, A graphical method to evaluate predominant geochemical processes occurring in groundwater systems for radiocarbon dating: Chemical Geology, v. 318–319, p. 88–112, accessed November 16, 2021, at https://doi.org/10.1016/j.chemgeo.2012.05.004.

Helsel, D.R., 2012, Statistics for censored environmental data using Minitab and R (2d ed.): Hoboken, N.J., Wiley, 324 p.

Helsel, D.R., 2016, Calculating uscores in R: Practical Stats web page, accessed January 9, 2017, at https://www.practicalstats.com/nada/downloads_files/.

Helsel, D.R., Hirsch, R.M., Ryberg, K.R., Archfield, S.A., and Gilroy, E.J., 2020, Statistical methods in water resources: U.S. Geological Survey Techniques and Methods, book 4, chap. A3, 458 p., accessed February 25, 2022, at https://doi.org/10.3133/tm4a3. [Supersedes USGS Techniques of Water-Resources Investigations, book 4, chap. A3, version 1.1.]

Hem, J.D., 1992, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Horton, J.D., 2017, The State Geologic Map Compilation (SGMC) geodatabase of the conterminous United States (ver. 1.1, August 2017): U.S. Geological Survey data release, accessed November 4, 2021, at https://doi.org/10.5066/F7WH2N65.

Houston, N.A., Thomas, J.V., Foster, L.K., Pedraza, D.E., and Welborn, T.L., 2021, Hydrogeologic framework and groundwater characterization in selected alluvial basins in the upper Rio Grande basin, Colorado, New Mexico, and Texas, United States, and Chihuahua, Mexico, 1980 to 2015: U.S. Geological Survey Scientific Investigations Report 2021–5035, 71 p., accessed May 26, 2023, at https://doi.org/10.3133/sir20215035.

Hu, X.C., Andrews, D.Q., Lindstrom, A.B., Bruton, T.A., Schaider, L.A., Grandjean, P., Lohmann, R., Carignan, C.C., Blum, A., Balan, S.A., Higgins, C.P., and Sunderland, E.M., 2016, Detection of poly- and perfluoroalkyl substances (PFASs) in US drinking water linked to industrial sites, military fire training areas, and wastewater treatment plants: Environmental Science & Technology Letters, v. 3, p. 344–350.

Intellus New Mexico, 2020, Quick search: Intellus New Mexico web page, accessed June 2, 2020, at https://www.intellusnm.com/reporting/quick-search/quick-search.cfm. [Data providers: Los Alamos National Laboratory, NMED DOE Oversight Bureau; Type of data: Analytical results; Type of samples: Water, Type of water: Base Flow, Ground Water, Water; Time period: June 2, 2015, to June 2, 2020; Where: Everywhere in the Los Alamos area; Analytical parameters: Select parameters from at list: Parameter Group: PFAS; Data Columns: default selected fields.]

Interstate Technology Regulatory Council, 2023, PFAS—Per- and polyfluoroalkyl substances—11 Sampling and Analysis: Interstate Technology Regulatory Council web page, accessed February 16, 2023, at https://pfas-1.itrcweb.org/11-sampling-and-analytical-methods/.

Jolliffe, I.T., and Cadima, J., 2016, Principal component analysis—A review and recent developments: Philosophical Transactions of the Royal Society A, Mathematical, Physical, and Engineering Sciences, v. 374, no. 2065, article 20150202.

Jurgens, B., Faulkner, K., McMahon, P.B., Hunt, A., Casile, G.C., Young, M.B., and Belitz, K., 2022, Over a third of groundwater in USA public-supply aquifers is Anthropocene-age and susceptible to surface contamination: Nature Communications Earth & Environment, v. 3, article 153, 9 p., accessed September 19, 2022, at https://doi.org/10.1038/s43247-022-00473-y.

Jurgens, B.C., 2018, Data for tritium deposition in precipitation in the United States, 1953–2012: U.S. Geological Survey data release, https://doi.org/10.5066/P92CEFXN.

Jurgens, B.C., McMahon, P.B., Chapelle, F.H., and Eberts, S.M., 2009, An Excel workbook for identifying redox processes in ground water: U.S. Geological Survey Open-File Report 2009–1004, 8 p. [Also available at http://pubs.usgs.gov/of/2009/1004.]

Kendall, C., Sklash, M.G., and Bullen, T.D., 1995, Isotope tracers of water and solute sources in catchments, *in* Trudgill, S.T., ed., Solute modeling in catchment systems: New York, Wiley, p. 261–303.

Kuroda, K., Murakami, M., Oguma, K., Takada, H., and Takizawa, S., 2014, Investigating sources and pathways of perfluoroalkyl acids (PFAAs) in aquifers in Tokyo using multiple tracers: Science of the Total Environment, v. 488−489, p. 51−60, accessed April 28, 2022, at https://doi.org/10.1016/j.scitotenv.2014.04.066.

Land, L., and Newton, B.T., 2008, Seasonal and long-term variation in hydraulic head in a karstic aquifer—Roswell Artesian Basin, New Mexico: Journal of the American Water Resources Association, v. 44, p. 175–191, accessed September 21, 2022, at https://doi.org/10.1111/j.1752-1688.2007.00146.x.

Langman, J.B., and Ellis, A.S., 2010a, A multi-isotope (δD, δ^{18}O, ^{87}Sr/^{86}Sr, and δ^{11}B) approach for identifying saltwater intrusion and resolving groundwater evolution along the western caprock escarpment of the Southern High Plains, New Mexico: Applied Geochemistry, v. 25, p. 159–174.

Langman, J.B., and Ellis, A.S., 2010b, Geologic influences on source-water mixing along a paleochannel in the Southern High Plains aquifer, New Mexico: Carbonates and Evaporites, v. 25, p. 247–265.

Langman, J.B., and O’Nolan, E.O., 2005, Streamflow and water-quality trends of the Rio Chama and Rio Grande, northern and central New Mexico, water years 1985 to 2002: U.S. Geological Survey Scientific Investigations Report 2005–5118, 42 p., accessed September 29, 2022, at https://pubs.usgs.gov/sir/2005/5118/.

Lee, L., 2017, Package ‘NADA’—Nondetects and data analysis for environmental data, version 1.6-1: Comprehensive R Archive Network web page, accessed April 26, 2022, at https://cran.r-project.org/web/packages/NADA/NADA.pdf.

Lenka, S.P., Kah, M., and Lokesh, P., 2021, A review of the occurrence, transformation, and removal of poly- and perfluoroalkyl substances (PFAS) in wastewater treatment plants: Water Research, v. 199, article 117187, 22 p., accessed September 21, 2022, at https://doi.org/10.1016/j.watres.2021.117187.

Lindsey, B.D., Jurgens, B.C., and Belitz, K., 2019, Tritium as an indicator of modern, mixed, and premodern groundwater age: U.S. Geological Survey Scientific Investigations Report 2019–5090, 18 p., accessed March 24, 2022, at https://doi.org/10.3133/sir20195090.

Lindstrom, A.B., Strynar, M.J., and Libelo, E.L., 2011, Polyfluorinated compounds—Past, present, and future: Environmental Science & Technology, v. 45, p. 7954–7961.

Manning, A.H., Solomon, K.D., and Thiros, S.A., 2005, ^{3}H/^{3}He age data in assessing the susceptibility of wells to contamination: Ground Water, v. 43, no. 3, p. 353–367, accessed April 28, 2022, at https://doi.org/10.1111/j.1745-6584.2005.0028.x.

McMahon, P.B., 2012, Use of classes based on redox and groundwater age to characterize the susceptibility of principal aquifers to changes in nitrate concentrations, 1991 to 2010: U.S. Geological Survey Scientific Investigations Report 2012–5220, 41 p., accessed April 28, 2022, at https://doi.org/10.3133/sir20125220.

Meals, D.W., Richards, R.P., and Dressing, S.A., 2013, Pollutant load estimation for water quality monitoring projects—Tech Notes 8, April 2013: U.S. Environmental Protection Agency, prepared by Tetra Tech, Inc., Fairfax, Va., 21 p., accessed September 3, 2019, at https://cran.r-project.org/web/packages/NADA/NADA.pdf.

Medalie, L., Baker, N.T., Shoda, M.E., Stone, W.W., Meyer, M.T., Stets, E.G., and Wilson, M., 2020, Influence of land use and region on glyphosate and aminomethylphosphonic acid in streams in the USA: Science of the Total Environment, v. 707, article 136008, 9 p., accessed February 11, 2022, at https://doi.org/10.1016/j.scitotenv.2019.136008.

Michel, R.L., Jurgens, B.C., and Young, M.B., 2018, Tritium deposition in precipitation in the United States, 1953–2012: U.S. Geological Survey Scientific Investigations Report 2018–5086, 11 p., accessed March 24, 2022, at https://doi.org/10.3133/sir20185086.

Miller, J.A., 2000, Ground water atlas of the United States: U.S. Geological Survey Hydrologic Investigations Atlas HA–730, accessed March 24, 2022, at https://pubs.usgs.gov/ha/ha730/.

Moeser, C.D., Chavarria, S.B., and Wootten, A.M., 2021, Streamflow response to potential changes in climate in the Upper Rio Grande Basin: U.S. Geological Survey Scientific Investigations Report 2021–5138, 41 p., accessed April 21, 2022, at https://doi.org/10.3133/sir20215138.

Mueller, D.K., Schertz, T.L., Martin, J.D., and Sandstrom, M.W., 2015, Design, analysis, and interpretation of field quality-control data for water-sampling projects: U.S. Geological Survey Techniques and Methods, book 4, chap. C4, 54 p., accessed April 21, 2022, at https://doi.org/10.3133/tm4C4.

Natural Resources Conservation Service, 2022, Rapid watersheds assessments: Natural Resources Conservation Service web page, accessed December 10, 2021, at https://www.nrcs.usda.gov/wps/portal/nrcs/main/nm/technical/dma/rwa/.

New Mexico Environment Department, 2020, PFAS data: New Mexico Environment Department web page, accessed June 2, 2020, at https://www.env.nm.gov/pfas/data/.

New Mexico Office of the State Engineer/Interstate Stream Commission, 2018, New Mexico State Water Plan part II—Technical report: New Mexico Office of the State Engineer, prepared by the New Mexico Interstate Stream Commission, 126 p., accessed April 27, 2022, at https://www.ose.state.nm.us/Planning/SWP/2018/3-2018_SWP_Part_II_Technical_Report_plusAppendixes.pdf.

New Mexico Water Data, 2022, NPDES permits: New Mexico Water Data web page, accessed January 24, 2022, at https://catalog.newmexicowaterdata.org/en_AU/dataset/new-mexico-npdes-permits.

Oklahoma History Center, 2022, The encyclopedia of Oklahoma history and culture: Oklahoma Historical Society web page, accessed April 12, 2022, at https://www.okhistory.org/publications/enc/entry.php?entry=CA039.

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Henry, M., Stevens, H., Szoecs, E., and Wagner, H., 2016, Package 'vegan'—Community ecology package (ver. 2.4–1): Comprehensive R Archive Network web page, accessed December 12, 2016, at https://cran.r- project.org/web/packages/vegan/index.html.

Östlund, H.G., 1987, Tritium: GEOSECS Atlantic, Pacific, and Indian Ocean Expeditions, v. 7, p. 7–10.

Parkhurst, D.L., and Charlton, S.R., 2008, NetpathXL—An Excel interface to the program NETPATH: U.S. Geological Survey Techniques and Methods, book 6, chap. A26, 11 p., accessed September 22, 2022, at https://doi.org/10.3133/tm6A26.

Patton, C.J., and Kryskalla, J.R., 2011, Colorimetric determination of nitrate plus nitrite in water by enzymatic reduction, automated discrete analyzer methods: U.S. Geological Survey Techniques and Methods, book 5, chap. B8, 34 p., accessed September 22, 2022, at https://doi.org/10.3133/tm5B8.

Pfaff, J.D., 1993, Method 300.0—Determination of inorganic anions by ion chromatography (rev. 2.1, August 1993): U.S. Environmental Protection Agency, Office of Research and Development, Environmental Monitoring Systems Laboratory, 30 p.

Piper, D.Z., and Bau, M., 2013, Normalized rare earth elements in water, sediments, and wine—Identifying sources and environmental redox conditions: American Journal of Analytical Chemistry, v. 4, no. 10, p. 69–83, accessed July 13, 2022, at https://doi.org/10.4236/ajac.2013.410A1009.

Plummer, L.N., Bexfield, L.M., Anderholm, S.K., Sanford, W.E., and Busenberg, E., 2012, Geochemical characterization of ground-water flow in the Santa Fe group aquifer system, Middle Rio Grande Basin, New Mexico (ver. 1.2): U.S. Geological Survey Water-Resources Investigations Report 03–4131, 395 p. [Also available at https://doi.org/10.3133/wri034131.]

R Core Team, 2023, R—A language and environment for statistical computing, version 4.2.3:Vienna, Austria, R Foundation for Statistical Computing software release, accessed October 4, 2023, at https://www.R-project.org/.

Révész, K., and Coplen, T.B., 2008a, Determination of the δ^{2}H/^{1}H, of water—RSIL lab code 1574: U.S. Geological Survey Techniques and Methods, book 10, chap. C1, 27 p., accessed January 13, 2020, at https://doi.org/10.3133/tm10C1.

Révész, K., and Coplen, T.B., 2008b, Determination of the $\delta^{18}O/^{16}O$ of water—RSIL lab code 489: U.S. Geological Survey Techniques and Methods, book 10, chap. C2, 28 p., accessed January 13, 2020, at https://doi.org/10.3133/tm10C2.

Rice, J., and Westerhoff, P., 2017, High levels of endocrine pollutants in US streams during low flow due to insufficient wastewater dilution: Nature Geoscience, v. 10, p. 587–591, accessed April 7, 2022, at https://doi.org/10.1038/NGEO2984.

Robertson, A.J., Ranalli, A.J., Austin, S.A., and Lawlis, B.R., 2016, The source of groundwater and solutes to Many Devils Wash at a former uranium mill site in Shiprock, New Mexico: U.S. Geological Survey Scientific Investigations Report 2016–5031, 54 p.

Robson, S.G., and Banta, E.R., 1995, Ground Water Atlas of the United States—Segment 2, Arizona, Colorado, New Mexico, Utah: U.S. Geological Survey Hydrologic Atlas 730–C, 32 p., accessed November 15, 2021, at https://doi.org/10.3133/ha730C.

Rozanski, K., Araguás-Araguás, L., and Gonfiantini, R., 1993, Isotopic patterns in modern global precipitation: Geophysical Monograph, v. 78, p. 1–36, accessed February 27, 2021, at https://doi.org/10.1029/GM078p0001.

Shephard, Z.M., Conn, K.E., Beisner, K.R., Jornigan, A.D., and Bryant, C.F., 2019, Characterization and load estimation of polychlorinated biphenyls (PCBs) from selected Rio Grande tributary stormwater channels in the Albuquerque urbanized area, New Mexico, 2017–18: U.S. Geological Survey Open-File Report 2019–1106, 48 p., accessed September 29, 2022, at https://doi.org/10.3133/of20191106.

Stewart, A.M., 2018, Hydrologic assessment and numerical simulation of groundwater flow, San Juan Mine, San Juan County, New Mexico, 2010–13: U.S. Geological Survey Scientific Investigations Report 2017–5155, 94 p., accessed November 16, 2021, at https://doi.org/10.3133/sir20175155.

Stuiver, M., and Polach, H.A., 1977, Discussion reporting of ^{14}C data: Radiocarbon, v. 19, p. 355–363, accessed September 22, 2022, at https://doi.org/10.1017/S0033822200003672.

U.S. Environmental Protection Agency [EPA], 2018, Method 537.1—Determination of selected per- and polyfluorinated alkyl substances in drinking water by solid phase extraction and liquid chromatography/tandem mass spectrometry (LC/MS/MS): U.S. Environmental Protection Agency web page, 50 p., accessed June 2, 2020, at https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=343042&Lab=NERL.

U.S. Environmental Protection Agency [EPA], 2020, Basic information on PFAS—What are PFAS?: U.S. Environmental Protection Agency web page, accessed May 1, 2020, at https://www.epa.gov/pfas/basic-information-pfas#health.

U.S. Environmental Protection Agency [EPA], 2022a, Drinking water health advisories for PFOA and PFOS: U.S. Environmental Protection Agency web page, accessed April 7, 2022, at https://www.epa.gov/ground-water-and-drinking-water/drinking-water-health-advisories-pfoa-and-pfos.

U.S. Environmental Protection Agency [EPA], 2022b, National PFAS datasets: U.S. Environmental Protection Agency web page, accessed March 24, 2022, at https://echo.epa.gov/tools/data-downloads/national-pfas-datasets.

U.S. Environmental Protection Agency [EPA], 2022c, San Juan Watershed Program: U.S. Environmental Protection Agency web page, accessed February 8, 2022, at https://storymaps.arcgis.com/collections/cf0c0658ae114e57a720c0c0c0e1b28b?item=1.

U.S. Environmental Protection Agency [EPA], 2022d, Third unregulated contaminant monitoring rule: U.S. Environmental Protection Agency web page, accessed June 24, 2022, at https://www.epa.gov/dwucmr/third-unregulated-contaminant-monitoring-rule.

U.S. Environmental Protection Agency [EPA], 2022e, NPDES permit basics: U.S. Environmental Protection Agency web page, accessed June 24, 2022, at https://www.epa.gov/npdes/npdes-permit-basics.

U.S. Environmental Protection Agency [EPA], 2023, Drinking water contaminants: U.S. Environmental Protection Agency database, accessed May 24, 2023, at https://www.epa.gov/ground-water-and-drinking-water/national-primarydrinking-water-regulations.

U.S. Geological Survey [USGS], 2022a, 3D Elevation Program 1-meter resolution digital elevation model: U.S. Geological Survey web page, accessed October 23, 2019, at https://www.usgs.gov/the-national-map-data-delivery.

U.S. Geological Survey [USGS], 2022b, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed April 28, 2022, at https://doi.org/10.5066/F7P55KJN.

U.S. Geological Survey [USGS], [variously dated], National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1–A10. [Also available online at http://pubs.water.usgs.gov/twri9A.]

Wang, Z., DeWitt, J.C., Higgins, C.P., and Cousins, I.T., 2017, A never-ending story of per- and polyfluoroalkyl substances (PFASs)?: Environmental Science & Technology, v. 51, p. 2508–2518.

Weishaar, J.L., Aiken, G.R., Bergamaschi, B.A., Fram, M.S., Fujii, R., and Mopper, K., 2003, Evaluation of specific ultraviolet absorbance as an indicator of the chemical composition and reactivity of dissolved organic carbon: Environmental Science & Technology, v. 37, p. 4702–4708.

Appendix 1. Water-Quality Data for Groundwater and Surface-Water Samples

Appendix tables 1.1–1.4 are available online in Excel (.xls) and comma-separated-value (.csv) format at https://doi.org/10.3133/sir20235129.

For more information about this publication, contact
Director, New Mexico Water Science Center
U.S. Geological Survey
6700 Edith Blvd. NE
Albuquerque, NM 87113

For additional information, visit
https://www.usgs.gov/centers/nm-water

Publishing support provided by
Lafayette Publishing Service Center

D9.111

Travis and others—**Assessment of Per- and Polyfluoroalkyl Substances in Water Resources of New Mexico, 2020–21**—SIR 2023–5129, ver. 1.2

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20235129

International Union of Pure and Applied Chemistry

Compendium of Chemical Terminology

Gold Book

Version 2.3.3
2014-02-24

NMOGA Exhibit D10

Index