BP Experience

- ☐ Capital investment ~ $1.4 million on portable three phase separators, sand traps and tanks
- ☐ Used Green Completions on 106 wells
- ☐ Total natural gas recovered ~ 350 million cubic feet per year (MMcf/yr)
- ☐ Total condensate recovered ~ 6,700 Bbl/yr

BP Experience

- ☐ Total value of natural gas and condensate recovered
  ~ $840,000 per year
- ☐ Investment recovered in 2+ years

Portable Three Phase Separator, Source: BP

Note:

- Value of natural gas at $1.99/Mcf
- Value of condensate at $22/Bbl

Devon Energy Experience

- Implemented Reduced Emission Completion (REC) in the Fort Worth Basin
- REC performed on 30 wells at an average incremental cost of $8,700
- Average 11,900 Mcf of natural gas sold vs. vented per well
  - **Natural gas flow and sales occur 9 days out of 2 to 3 weeks of well completion**
  - **Low pressure gas sent to gas plant**
  - **Conservative net value of gas saved is $50,000 per well**
- Expects emission reduction of 1.5 to 2 Bcf in year 2005

Weatherford Durango Experience

- ☐ Successfully completed pilot project in the Fruitland coal formations in Durango, Colorado
  - ◆ **Well depth: 2,700 to 3,200 feet**
  - ◆ **Pore pressure: estimated at 80 pounds per square inch gauge (psig)**
  - ◆ **Well type: coal bed methane**
  - ◆ **Hole size: 5 ½ inches**
  - ◆ **No. of wells: 3 well pilots**

- ☐ Captured 2 MMcf of gas and sold by client

Weatherford Portable Equipment

Weatherford Green Completions

- ☐ Use natural gas from pipeline along with proprietary foaming agent as compressible fluid to initiate cleanout
- ☐ Cleaning system consists of a wet screw compressor in addition to the booster, three phase separator and sand trap
  - ◆ **Wet screw compressor used when well pressure is less than 80 psig**
- ☐ Estimate a clean up pressure of 300 to 400 psig at a well depth of 8000 feet
- ☐ Suggests use in all kinds of completion and workover cleanup operations

Discussion Questions

- ☐ To what extent are you implementing this opportunity?
- ☐ Can you suggest other approaches for reducing well venting?
- ☐ How could these opportunities be improved upon or altered for use in your operation?
- ☐ What are the barriers (technological, economic, lack of information, regulatory, focus, manpower, etc.) that are preventing you from implementing this practice?

Lessons Learned
from Natural Gas STAR Partners

Reduced Emissions Completions for Hydraulically Fractured Natural Gas Wells

Executive Summary

In recent years, the natural gas industry has developed more technologically challenging unconventional gas reserves such as tight sands, shale and coalbed methane. Completion of new wells and re-working (workover) of existing wells in these tight formations typically involve hydraulic fracturing of the reservoir to increase well productivity. Industry reports that hydraulic fracturing is beginning to be performed in some conventional gas reservoirs as well. Removing the water and excess proppant (generally sand) during completion and well clean-up may result in significant releases of natural gas and therefore methane emissions to the atmosphere. The *U.S. Inventory of Greenhouse Gas Emissions and Sinks 1990 - 2009* estimates that 68 billion cubic feet (Bcf) of methane are vented or flared annually from unconventional completions and workovers.

Reduced emissions completions (RECs) – also known as reduced flaring completions or green completions – is a term used to describe an alternate practice that captures gas produced during well completions and well workovers following hydraulic fracturing. Portable equipment is brought on site to separate the gas from the solids and liquids produced during the high-rate flowback, and produce gas that can be delivered into the sales pipeline. RECs help to reduce methane, VOC, and HAP emissions during well cleanup and can eliminate or significantly reduce the need for flaring.

RECs have become a popular practice among Natural Gas STAR production partners. A total of thirteen different partners have reported performing reduced emissions completions in their operations. RECs have become a major source of methane emission reductions since 2000. Between 2000 and 2009 emissions reductions from RECs (as reported to Natural Gas STAR) have increased from 200 MMcf (million cubic feet) to over 218,000 MMcf. Capturing an additional 218,000 MMcf represents additional revenue from natural gas sales of over $1.5 billion from 2000 to 2009 (assuming $7/Mcf gas prices).

Technology Background

High demand and higher prices for natural gas in the U.S. have resulted in increased drilling of new wells in more expensive and more technologically challenging unconventional gas reservoirs, including those in low porosity (tight) formations. These same high demands and

Economic and Environmental Benefits

Method for Reducing Natural Gas Losses	Volume of Natural Gas Savings (Mcf)	Value of Natural Gas Savings ($)			Additional Savings ($)	Implementation Cost ($)	Other Costs ($)	Payback (Months)		
		$3 per Mcf	$5 per Mcf	$7 per Mcf				$3 per Mcf	$5 per Mcf	$7 per Mcf
Purchased REC Equipment Annual Program	270,000 per year	$810,000 per year	$1,350,000 per year	$1,890,000 per year	$175,000 per year	$500,000	$121,250 per year	6	4	3
Incremental REC Contracted Service	10,800 per completion	$32,400 per completion	$54,000 per completion	$75,600 per completion	$6,930 per completion	$32,400	$600 per completion	Immediate	Immediate	Immediate

General Assumptions:
* Assuming 9 days per completion, 1,200 Mcf gas savings per day per well, 11 barrels of condensate recovered per day per well, and cost of $3,600 per well per day for contra
[1] Assuming $70 per barrel of condensate.
[2] Based on an annual REC program of 25 completions per year.

CA Ex. 14
Ex. 10

prices also justify extra efforts to stimulate production from existing wells in tight reservoirs where the down-hole pressure and gas production rates have declined, a process known as well workovers or well-reworking. In both cases, completions of new wells in tight formations and workovers of existing wells, one technique for improving gas production is to fracture the reservoir rock with very high pressure water containing a proppant (generally sand) that keeps the fractures "propped open" after water pressure is reduced. Depending on the depth of the well, this process is carried out in several stages, usually completing one 200- to 250-foot zone per stage.

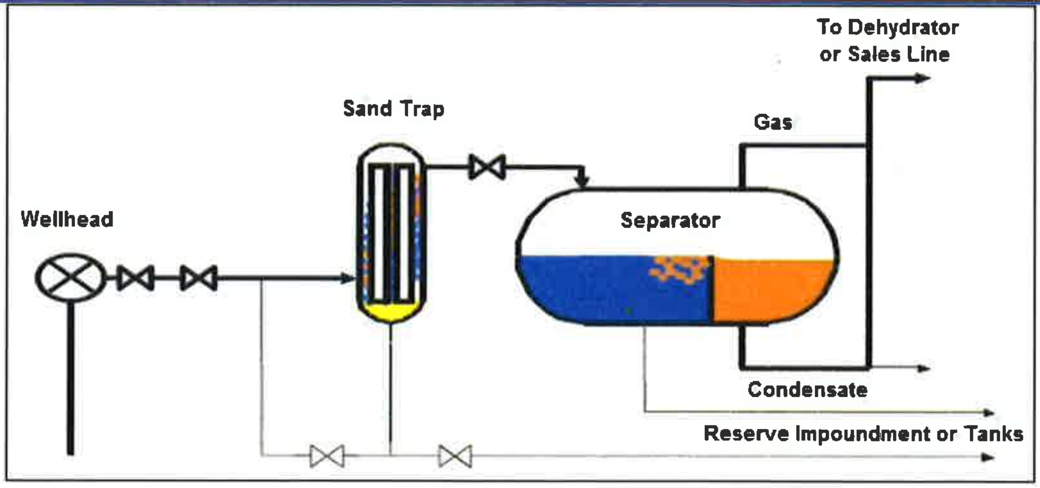
These new and "workover" wells are completed by producing the fluids at a high rate to lift the excess sand to the surface and clear the well bore and formation to increase gas flow. Typically, the gas/liquid separator installed for normal well flow is not designed for these high liquid flow rates and three-phase (gas, liquid and sand) flow. Therefore, a common practice for this initial well completion step has been to produce the well to a pit or tanks where water, hydrocarbon liquids and sand are captured and slugs of gas vented to the atmosphere or flared. Completions can take anywhere from one day to several weeks during which time a substantial amount of gas may be released to the atmosphere or flared. Testing of production levels occurs during the well completion process, and it may be necessary to repeat the fracture process to achieve desired production levels from a particular well.

Natural gas lost during well completion and testing can be as much as 25 million cubic feet (MMcf) per well depending on well production rates, the number of zones completed, and the amount of time it takes to complete each zone. This gas is generally unprocessed and may contain volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) along with methane. Flaring gas may eliminate most methane, VOC and HAP emissions, but open flaring is not always a preferred option when the well is located near residential areas or where there is a high risk of grass or forest fires. Moreover, flaring may release additional carbon dioxide and other criteria pollutants (SOx, NOx, PM and CO) to the atmosphere.

Natural Gas STAR partners have reported performing RECs that recover much of the gas that is normally vented or flared during the completion process. This involves installing portable equipment that is specially designed and sized for the initial high rate of water, sand, and gas flowback during well completion. The objective is to capture and deliver gas to the sales line rather than venting or flaring this gas.

Sand traps are used to remove the finer solids present in the production stream. Plug catchers are used to remove any large solids such as drill cuttings that could damage the other separation equipment. The piping configuration to the sand traps is critical as the abrasion from high velocity water and sand can erode a hole in steel pipe elbows, creating a "washout" with water, sand,

Exhibit 1: Reduced Emissions Completion Equipment Layout



Adapted from BP.

hydrocarbon liquids and gas in an uncontrolled flow to the pad. Depending on the gas gathering system, it may be necessary to dehydrate (remove water from) the produced gas before it enters the sales pipeline. The gas may be routed to the permanent glycol unit for dehydration or a portable desiccant/glycol dehydrator used for dehydration during the completion process.

Free water and condensate are removed from the gas in a three phase separator. Condensate (liquid hydrocarbons) collected during the completion process may be sold for additional revenue. Temporary piping may be used to connect the well to the REC skid and gathering system if the permanent piping is not yet in place. Exhibit 1 shows a typical layout of temporary REC portable equipment, and Exhibit 2 explains some alternate, emerging, and/or experimental procedures for a well completion and REC.

Exhibit 2: Alternate Completion Procedures

Energized Fracturing

Based on Natural Gas STAR partner experiences, RECs can also be performed in combination with energized fracturing, wherein inert gas such as CO_2 or nitrogen is mixed with the frac water under high pressure to aid in the process of fracturing the formation. The process is generally the same with the additional consideration of the composition of the flowback gas. The percent of inert gases in the flowback gas is, at first, unsuitable for delivery into the sales line. As the fraction of inerts decreases, the gas can be recovered economically. A portable membrane acid gas separation unit can further increase the amount of methane recovered for sales after a CO_2 energized fracture.

Compression

Two compressor applications during an REC have been identified or explored by Natural Gas STAR partners.

1) Gas Lift. In low pressure (i.e. low energy) reservoirs RECs are often carried out with the aid of compressors for gas lift. Gas lift is accomplished by withdrawing gas from the sales line, boosting its pressure, and routing it down the well casing to push the frac fluids up the tubing. The increased pressure facilitates flow into the separator and then the sales line where the lift gas becomes part of the normal flowback that can be recovered during an REC.

2) Boost to Sales Line. When the gas recovered in the REC separator is lower pressure than the sales line, some companies are experimenting with a compressor to boost flowback gas into the sales line. This technique is experimental because of the difficulty operating a compressor on widely fluctuating flowback rate. Coal bed methane well completion is an example where additional compression might be required.

The equipment used during RECs is only necessary for the time it takes to complete the well; therefore, it is essential that all the equipment can be readily transported from site to site to be used in a number of well completions. A truck mounted skid, as shown in Exhibit 3, is ideal for transporting the equipment between sites. In a large basin that has a high level of drilling activity it may be economic for a gas producer to build its own REC skid. Most producers may prefer contracting a third party service to perform completions.

When using a third party to perform RECs, it is most cost effective to integrate the scheduling of completions with the annual drilling program. Well completion time is another factor to consider for scheduling a contractor for RECs. Some well completions, such as coal bed methane, may take less than a day. On the other hand, completing wells which fracture various zones, such as shale gas wells, may take several weeks to complete. For most wells, it takes about 3 to 10 days to perform a well completion following a hydraulic fracture, based on partner experiences.

Exhibit 3: Truck Mounted Reduced Emissions Completion Equipment

Source: Weatherford

Economic and Environmental Benefits

- ★ Gas recovered for sales
- ★ Condensate recovered for sales
- ★ Reduced methane emissions

- Reduced loss of a valuable hydrocarbon resource
- Reduced emissions of criteria and hazardous air pollutants

Emissions from well completions can contribute to a number of environmental problems. Direct venting of VOCs can contribute to local air pollution, HAPs are deemed harmful to human health, and methane is a powerful greenhouse gas that contributes to climate change. Where it is safe, flaring is preferred to direct venting because methane, VOCs, and HAPs are combusted, lowering pollution levels and reducing global warming potential (GWP) of the emissions as CO_2 from combustion has a lower GWP than methane. RECs allow for recovery of gas rather than venting or flaring and therefore reduce the environmental impact of well completion and workover activities.

RECs bring economic benefits as well as environmental benefits. The incremental costs associated with the rental of third party equipment for performing RECs can be offset by the additional revenue from the sale of gas and condensate. As this technology is being perfected and equipment becomes commonplace, the revenues in gas and condensate sales often exceed the incremental costs.

Decision Process

Step 1: Evaluate candidate wells for Reduced Emissions Completions.

When setting up an annual RECs program it is important to examine the characteristics of the wells that are going to be brought online in the coming year. Wells in conventional reservoirs that do not require a reservoir fracture (frac job) and will produce readily without stimulation can be cleared of drilling fluids and connected to a production line in a relatively short period of time with minimal gas venting or flaring, and therefore usually do not economically justify REC equipment. Wells that undergo energized fracture using inert gases require special considerations because the initial produced gas captured by the REC equipment would not meet pipeline specifications due to the inert gas content. However, as the amount of inerts decreases, the quality of the gas will likely meet pipeline specifications. In the case of CO_2 energized fracks, the use of portable acid gas removal membrane separators will improve gas quality and make it possible to direct gas to the pipeline (see Partner Experiences section for more information).

Decision Process
Step 1: Evaluate candidate wells
Step 2: Determine costs
Step 3: Estimate savings
Step 4: Evaluate economics

State and Local Regulations
The States of Wyoming and Colorado have regulations requiring the implementation of "flareless completions". Operators of new wells in this region are required to complete wells without flaring or venting. These completions have reduced flaring by 70 to 90 percent.

For more information, visit:
http://deq.state.wy.us
http://www.cdphe.state.co.us

Exploratory and delineation wells in areas that do not yet have sales pipelines in close proximity to the wells are not candidates for RECs as the infrastructure is not in place to receive the recovered gas. In depleted or low pressure fields with low energy reservoirs, implementing a RECs program would most likely require the addition of compression to overcome the sales line pressures–an approach that is still under development and may add significant cost to implementation.

Wells that require hydraulic fracturing to stimulate or enhance gas production may need a lengthy completion, and therefore are good candidates for RECs. Lengthy completions mean that a significant amount of gas may be vented or flared that could potentially be recovered and sold for additional revenue to justify the additional cost of a REC. If newly drilled wells are in close proximity, they could share the REC equipment to minimize transport, set-up, and equipment rental costs.

Selecting a Basis for Costs and Savings

- Estimate the number of producing gas wells that will be drilled in the next year
- Evaluate well depth and reservoir characteristics
- Determine whether additional equipment is necessary to bring recovered gas up to pipeline specifications
- Estimate time needed for each completion

Step 2: Determine the costs of a REC program.

Most Natural Gas STAR partners report using third party contractors to perform RECs on wells within their producing fields. It should be noted that third party contractors are also often used to perform traditional well completions. Therefore, the economics presented deal with

Reduced Emissions Completions
(Cont'd)

incremental costs to carry out RECs versus traditional completions.

Generally, the third party contractor will charge a commissioning fee for transporting and setting up the equipment for each well completion within the operator's producing field. Some RECs vendors have their equipment mounted on a single trailer while others lay down individual skids that must be connected with temporary piping at each site. The incremental cost associated with transportation between well sites in the operator's field and connection of the REC equipment within the normal flowback piping from the wellhead to an impoundment or tank is generally around $600/completion.

In addition to the commissioning fee, there is a daily cost for equipment rental and labor to perform each REC. As mentioned above, when evaluating the costs of well completions, it is important to consider the incremental cost of a REC over a traditional completion rather than focusing on the total cost. REC vendors and Natural Gas STAR partners have reported the incremental cost of equipment rental and labor to recover natural gas during completion ranging from $700 to $6,500/day over a traditional completion. Equipment costs associated with RECs will vary from well to well. High production rates may require larger equipment to perform the REC and will increase costs. If permanent equipment such as a glycol dehydrator is already installed at the well site, REC costs may be reduced as this equipment can be used rather than bringing a portable dehydrator on-site, assuming the flow-back rate does not exceed the capacity of the equipment. Some operators report installing permanent equipment that can be used in the RECs as part of normal well completion operations, such as oversized three-phase separators, further reducing incremental REC costs. Well completions usually take between 1 to 30 days to clean out the well bore, complete well testing, and tie into the permanent sales line. Wells requiring multiple fractures of a tight formation to stimulate gas flow may require additional completion time. Exhibit 4 shows the typical costs associated with undertaking a REC at a single well.

Exhibit 4: Typical Costs for RECs

One-time Transportation and Incremental Set-up Costs	Incremental REC Equipment Rental and Labor Costs	Well Clean-up Time
$600 per well	$700 to $6,500 per day	3 to 10 days

For low energy reservoirs, gas from the sales line may be routed down the well casing to create artificial gas lift, as mentioned in Exhibit 2. Depending on the depth of the well, a different quantity of gas will be required to lift the fluids and clean out the well. Using average reservoir depths for major U.S. basins and engineering calculations, Exhibit 5 shows various estimates of the volume of gas required to lift fluids for different well depths.

A REC annual program may consist of completing 25 wells/year within a producer's operating region. Exhibit 6 shows a hypothetical example of REC program costs based on information provided by partner companies.

Exhibit 5: Sizing and Fuel Consumption for Booster Compressor

Well Depth (ft)	Pressure Required to Lift Fluids (psig)	Gas Required to Lift Fluids (Mcf)[a]	Compressor Size (horsepower)[a]	Compressor Fuel Consumption (Mcf/hr)[a]
3,000	1,319 + Sales line pressure	195 to 310	195 to 780	2 to 7
5,000	2,323 + Sales line pressure	315 to 430	400 to 1,500	3 to 13
8,000	3,716 + Sales line pressure	495 to 610	765 to 2,800	7 to 24
10,000	4,645 + Sales line pressure	615 to 730	1,040 to 3,900	9 to 33

[a] Based on sales line pressures between 100 to 1,000 psig

Exhibit 6: Hypothetical Example Cost Calculation of a 25 Well Annual REC Program

Given

W = Number of completions per year
D = Well depth in feet (ft)
P_s = Sales line pressure in pounds per square inch gauge (psig)
T_s = Time required for transportation and set-up (days/well)
T_c = Time required for well clean-up (days/well)
O = Operating time for compressor to lift fluids (hr/well)
F = Compressor fuel consumption rate (Mcf/hr)
G = Gas from pipeline routed to casing to lift fluids (Mcf/well), typically used on low energy reservoirs
C_s = Transportation and set-up cost ($/well)
C_e = Equipment and labor cost ($/day)
P_g = Sales line gas price ($/Mcf)

W = 25 wells/yr
D = 8000 ft
P_s = 100 psig
T_s = 1 day/well
T_c = 9 days/well
O = 24 hr/well
F = 10 Mcf/hr
G = 500 Mcf/well (See Exhibit 5)
C_s = $600/well
C_e = $2,000/day
P_g = $7/Mcf

Calculate Total Transportation and Set-up Cost, C_{TS}

$C_{TS} = W * C_s$

C_{TS} = 25 wells/yr * $600/well
C_{TS} = $15,000/yr

Calculate Total Equipment Rental and Labor Cost, C_{EL}

$C_{EL} = W * (T_s + T_c) * C_e$

C_{EL} = 25 wells/yr * (1 day/well + 9 days/well) * $2,000/day
C_{EL} = $500,000/yr

Calculate Other Costs, C_O

$C_O = W * [(O * F) + G] * P_g$

C_O = 25 wells/yr * [(24 hr/well * 10 Mcf/hr) + 500 Mcf/well] * $7/Mcf
C_O = $129,500/yr

Total Annual REC Program Cost, C_T

$C_T = C_{TS} + C_{EL} + C_O$
C_T = $15,000/yr + $500,000/yr + $129,500/yr
C_T = $644,500/yr

Step 3: Estimate Savings from RECs.

Gas recovered from RECs can vary widely because the amount of gas recovered depends on a number of variables such as reservoir pressure, production rate, amount of fluids lifted, and total completion time. Exhibit 7 shows the range of recovered gas and condensate reported by Natural Gas STAR partners. Partners also have reported that not all the gas that is produced during well completions may be captured for sales. Fluids from high pressure wells are often routed directly to the frac tank in the initial stages of completion as the fluids are often being produced at a rate that is too high for the REC equipment. Where inert gas is used to energize the frac, the initial gas production may have to be flared until the gas meets pipeline specifications. Alternatively, a portable acid gas membrane separator may be used to recover methane rich gas from CO_2. As the flow rate of fluids drops and gas is encountered, backflow is then switched over to the REC equipment so that the gas may be captured. Gas compressed from the sales line to lift fluids (by artificial gas lift) will also be recovered in addition to the gas produced from the reservoir. The volume of gas needed to lift fluids can be estimated based on the well depth and sales line pressure. Gas saved during RECs can be translated directly into methane emissions reductions based on the methane content of the produced gas.

In addition to gas savings, valuable condensate may also be recovered from the REC three-phase separator. The amount of condensate that can be recovered during a REC is dependent on the reservoir conditions and fluid compositions. Condensate may also be lost if fluids are produced directly to the frac tank before switching to the REC equipment.

Exhibit 7: Ranges of Gas and Condensate Savings

Produced Gas Savings (Mcf/day/well)	Gas-Lift Savings (Mcf/well)	Condensate Savings (bbl/day/well)
500 to 2,000	See Exhibit 5	Zero to several hundred

Exhibit 8 shows typical values of gas and condensate savings during the REC process.

Nelson Price Indexes

In order to account for inflation in equipment and operating & maintenance costs, Nelson-Farrar Quarterly Cost Indexes (available in the first issue of each quarter in the *Oil and Gas Journal*) are used to update costs in the Lessons Learned documents.

The "Refinery Operation Index" is used to revise operating costs while the "Machinery: Oilfield Itemized Refining Cost Index" is used to update equipment costs.

To use these indexes in the future, simply look up the most current Nelson-Farrar index number, divide by the February 2006 Nelson-Farrar index number, and, finally multiply by the appropriate costs in the Lessons Learned.

Step 4: Evaluate REC economics.

The example application of an REC program to 25 wells within a producing field can yield a total theoretical revenue of $2,152,500 based on the assumptions listed above from the sale of natural gas and condensate. Equipment rental, labor, and other costs associated with implementing this program are estimated to be $644,500 (see Exhibit 6) resulting in an annual theoretical profit of $1,508,000. To maintain a profitable REC program, it is important to move efficiently from well to well within a producing field so that there is little down time when paying for equipment rental and labor. Other factors that affect the profitability of an REC program include the amount of condensate recovery and sales price, the need for additional compressors, the amount of gas recovered, and gas sales price.

Exhibit 9 shows a five year cash flow projection for carrying out a 25 well per year REC program. In this example, the equipment necessary to perform RECs has been purchased by the operator rather than using a third party contractor to perform the service. The capital cost of a simple REC set-up without a portable compressor has been reported by British Petroleum (BP) to be $500,000.

Producers with high levels of localized drilling and workover activity may benefit from constructing and operating their own REC equipment. As illustrated above, even though large capital outlay is required to construct a REC skid, a high rate of return can be achieved if the equipment is in continuous use. If the operator is unable to keep the equipment busy on their own wells, they may

Exhibit 8: Savings of a 25 Well Annual REC Program

Given

W = Number of completions per year
D = Well depth in feet (ft)
P_s = Sales line pressure in pounds per square inch gage (psig)
S_p = Produced gas savings (Mcf/day)
T_c = Time recovered gas flows to sales line in days (days/well)
S_c = Condensate savings (bbl/well)
G = Gas used to lift fluids (Mcf/well), typically used on low energy reservoirs
P_g = Sales line gas price ($/Mcf)
P_l = Natural gas liquids price ($/bbl)

W = 25 wells/yr
D = 8000 ft
P_s = 100 psig
S_p = 1,200 Mcf/day
T_c = 9 days/well
S_c = 100 bbl/well
G = 500 Mcf/well (See Exhibit 5)
P_g = $7/Mcf
P_l = $70/bbl

Calculate Produced Gas Savings

$S_{PG} = W * (S_p * T_c) * P_g$

S_{PG} = 25 wells/yr * (1,200 Mcf/day * 9 days/well) * $7/Mcf
S_{PG} = $1,890,000/yr

Calculate Other Savings

$S_O = W * [(G * P_g) + (S_c * P_l)]$

S_O = 25 wells/yr * [(500 Mcf/well * $7/Mcf) + (100 bbl/well * $70/bbl)]
S_O = $262,500/yr

Total Savings, S_T

$S_T = S_{PG} + S_O$
S_T = $1,890,000/yr + $262,500/yr
S_T = $2,152,500/yr

contract it out to other operators to maximize usage of the equipment.

When assessing REC economics, the gas price may influence the decision making process; therefore, it is important to examine the economics of undertaking a REC program as natural gas prices change. Exhibit 10 shows an economic analysis of performing the 25 well per year REC program in Exhibit 8 at different gas prices.

Exhibit 9: Economics for Hypothetical 25 Well Annual REC Program with Purchased Equipment

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Volume of Natural Gas Savings (Mcf/yr)[a]		270,000	270,000	270,000	270,000	270,000
Value of Natural Gas Savings ($/year)[a]		1,890,000	1,890,000	1,890,000	1,890,000	1,890,000
Additional Savings ($/yr)[a]		175,000	175,000	175,000	175,000	175,000
Set-up Costs ($/yr)[b]		(15,000)	(15,000)	(15,000)	(15,000)	(15,000)
Equipment Costs ($)[b]	(500,000)					
Labor Costs ($/yr)[c]		(106,250)	(106,250)	(106,250)	(106,250)	(106,250)
Net Annual Cash Flow ($)	**(500,000)**	**1,943,750**	**1,943,750**	**1,943,750**	**1,943,750**	**1,943,750**

Internal Rate of Return = 389%
NPV (Net Present Value)[d]= $6,243,947
Payback Period = 3 months

[a] See Exhibit 8.
[b] See Exhibit 6.
[c] Labor costs for purchased REC equipment estimated as 50% of Equipment Rental and Labor costs in Exhibit 3.
[d] Net present value based on 10% discount rate over five years.

Exhibit 10: Gas Price Impact on Economic Analysis of Hypothetical 25 Well Annual REC Program with Purchased Equipment

	Gas Price				
	$3/Mcf	**$5/Mcf**	**$7/Mcf**	**$8/Mcf**	**$10/Mcf**
Total Savings	$985,000	$1,525,000	$2,065,000	$2,335,000	$2,875,000
Payback (months)	7	5	4	3	3
IRR	172%	280%	389%	443%	551%
NPV (i = 10%)	$2,522,084	$4,383,015	$6,243,947	$7,174,413	$9,035,345

Partner Experience

This section highlights specific experiences reported by Natural Gas STAR partners.

BP Experience in Green River Basin

- ★ Implemented RECs in the Green River Basin of Wyoming
- ★ RECs performed on 106 wells, which consisted of high and low pressure wells
- ★ Average 3,300 Mcf of natural gas sold versus vented per well
  - Well pressure will vary from reservoir to reservoir
  - Reductions will vary for each particular region
  - Conservative net value of gas saved is $20,000 per well
- ★ Natural gas emission reductions of 350,000 Mcf in 2002
- ★ Total of 6,700 barrels of condensate recovered per year total for 106 wells
- ★ Through the end of 2005, this partner reports a total of 4.17 Bcf of gas and more than 53,000 barrels of condensate recovered and sold rather than flared. This is a combination of activities in the Wamsutter and Jonah/Pinedale fields.

Noble Experience in Ellis County, Oklahoma

- ★ Implemented RECs on 10 wells using energized fracturing.
- ★ Employed membrane separation in which the permeate was a CO_2 rich stream that was vented and the residue was primarily hydrocarbons which were recovered.
- ★ Total cost of $325,000.
- ★ Total gas savings of approximately 175 MMcf.
- ★ Estimated net profits to be $340,000
- ★ For more information, see the Partner Profile Article in the Spring 2011 Natural Gas STAR Partner Update available at: http://epa.gov/gasstar/newsroom/partnerupdatespring2011.html

Partner Company A

- ★ Implemented RECs in the Fort Worth Basin of Texas
- ★ RECs performed on 30 wells, with an incremental cost of $8,700 per well
- ★ Average 11,900 Mcf of natural gas sold versus vented per well
  - Natural gas flow and sales occur 9 days out of 2 to 3 weeks of well completion
  - Low pressure gas sent to gas plant
  - Conservative net value of gas saved is $50,000 per well
- ★ Expects total emission reduction of 1.5 to 2 Bcf in 2005 for 30 wells

Lessons Learned

- ★ Incremental costs of recovering natural gas and condensate during well completions following hydraulic fracturing result from the use of additional equipment such as sand traps, separators, portable compressors, membrane acid gas removal units and desiccant dehydrators that are designed for high rate flowback.
- ★ During the hydraulic fracture completion process, sands, liquids, and gases produced from the well are separated and collected individually. Natural gas and gas liquids captured during the completion may be sold for additional revenue.
- ★ Implementing a REC program will reduce flaring which may be a particular advantage where open flaring is undesirable (populated areas) or unsafe (risk of fire).
- ★ Wells that do not require hydraulic fracturing are not good candidates for reduced emissions completions. Methane emissions reductions achieved through performing RECs may be reported to the Natural Gas STAR Program unless RECs are required by law (as in the Jonah-Pinedale area in WY).

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Reduced Emissions Completions
(Cont'd)

United States
Environmental Protection Agency
Air and Radiation (6202J)
1200 Pennsylvania Ave., NW
Washington, DC 20460

2011

EPA provides the suggested methane emissions estimating methods contained in this document as a tool to develop basic methane emissions estimates only. As regulatory reporting demands a higher-level of accuracy, the methane emission estimating methods and terminology contained in this document may not conform to the Greenhouse Gas Reporting Rule, 40 CFR Part 98, Subpart W methods or those in other EPA regulations.

Green Completions

Topic last reviewed: 1 February 2014

Sectors: Upstream

Well completion refers to the process that initiates the flow of petroleum or natural gas from a newly drilled well prior to production. This stream of fluids during well completions is referred to as "flowback". During completion the reservoir is connected to the wellbore allowing the flowback of drilling and reservoir fluids (gas, oil, water, mud, etc.) to the surface. In a conventional well completion, the flowback period (also known as well cleanup) may involve flaring or venting of produced gas to the atmosphere via an open pit or tank collecting the fluids.

Well completions that involve hydraulic fracturing result in a higher rate of flowback than most conventional well completions, due to the large quantities of water and proppant (mainly sand) used to fracture lower permeability reservoirs. This high-rate flowback is generally composed of a mixture of fracking fluids with reservoir gas and liquids. For most wells, it takes from one day to several weeks to perform a well completion, during which the flowback mixture is typically released to an open pit or tank where the gas released from the liquids is vented to the atmosphere or flared depending on regulatory requirements or other factors. If the gas is vented, this may generate a significant amount of methane and hydrocarbon emissions to the atmosphere. Similarly, flaring generates a significant amount of combustion emissions, incurs product losses and is not always a viable option depending on the well location, the concentration of flammable gases in the flowback gas and other considerations.

In order to offset the loss of methane and other hydrocarbons during flowback, a technolog
Reduced Emissions Completions (RECs) or "green completions" may be implemented. Gree
alternate practice that captures the produced gas during well completions and well workov

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hydraulic fracturing. Portable equipment **(Figure 1)** is brought temporarily to the well site to separate the gas from the liquids and solids in the flowback stream, producing a gas stream that is ready or nearly ready for the sales pipeline.

Figure 1. Truck-mounted green completions equipment. (Source: Weatherford. Natural Gas Star, 2010)

With green completions, a temporary system is used which consists of a skid or trailer mounted set of piping connections and vessels that include a plug catcher, a sand trap and a three phase separator **(Figure 2).** The plug catcher (not shown in **Figure 2**) is connected to the wellhead and is used to remove any large solids from the drilling and completion to avoid damaging other separation equipment [The sand trap removes finer solids present in the production stream, while the three phase separator removes water and condensate from the gas. Liquid hydrocarbons may be collected during completion and sold for additional revenue. Water is typically stored in water tanks or in a reserve impoundment for later treatment or disposal. If necessary, captured gas may enter a portable dehydrator at the well site or it may be routed to a permanent glycol dehydration unit in the gathering system, if one is available at or near the site, to remove heavy moisture from the gas before it enters the sales pipeline.

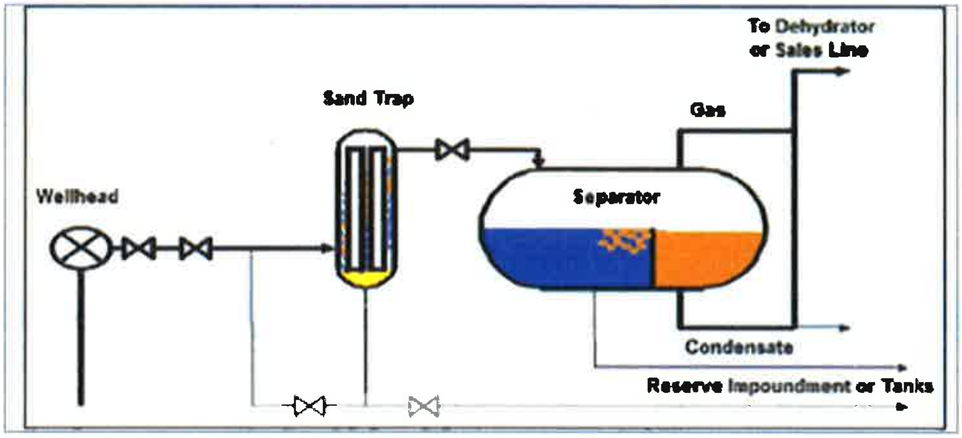

Figure 2. Green completions equipment layout (Source: Natural Gas Star, 2011. Adapted from BP)

The equipment used during green completions is only necessary for the duration of the well completion. Therefore, equipment that can be readily transported from one completion site to another is more commonly used. A truck-mounted skid (as shown in **Figure 1**) is often used for transporting the equipment between sites. Oil and gas producers may use a third party service provider that rents the equipment, sets it up, and performs the green completion; however, in a large basin with high levels of drilling activity, it may be more economic for a producer to invest in its own green completion skid and carry out the operation themselves.

Green completions can provide environmental and economic benefits to oil and gas operations. The incremental costs associated with the capital investment of acquiring green completion equipment, or equipment rental and labor cost from a third party provider can be offset by the additional revenue from the sale of gas and/or condensate. If the technology improves over time and equipment-related costs are reduced, the revenues in gas and condensate sales may exceed the incremental costs.

Application of Technology

It could be technically feasible but may not be economically viable as REC equipment would have to be transported to off-shore site, or be permanently installed. Industry experiences have not yet been recorded publicly. Also, offshore developments typically have much fewer wells than onshore, so the benefits would be smaller and the costs higher and therefore not necessarily economically viable.

Technology maturity

Commercially available?:	Yes

Offshore viability:	No
Brownfield retrofit?:	Yes
Years experience in the industry:	11-20

Key metrics

Range of application:	Well completions in unconventional gas formations (shale gas, tight sands, coal bed methane, or any low permeability, tight reservoir) involving hydraulic fracturing. Applicable for rehabilitation and redevelopment of mature wells (recompletions). Not recommended for low-pressure wells and exploratory (wildcat) wells located at long distances from a gathering system. Documentation recording the application of green completions in oil wells is not available. While green completions in oil wells may be technically feasible, it requires a gas pipeline infrastructure (and capacity) to be in place, which may not be the case in many oil formations. It could also be less economically feasible for oil wells as liquid hydrocarbon is the primary product instead of gas.
Efficiency:	Recovery of up to 90% of flow back gas
Guideline capital costs:	Purchased equipment one-time capital investment: around $500,000 for a simple REC set-up (values as of 2011). Payback time will depend on the amount of gas produced, gas prices and the utility rate (amount of wells completed per year) of the equipment. Payback time has been reported to be as little as 3 months by natural gas operators, but tends to be around one year on average [1].

Guideline operational costs: Third party contractors are often hired to perform conventional well completions. Many third party contractors also offer the equipment rental and labor to perform green well completions. Costs described here show are the incremental cost of using REC equipment - either hired ($600- $6,500/day) or purchased, and with labour costs only (~$300-$3,250/day), versus traditional methods of well completions. Costs vary per well depending on the characteristics of the flowback. High rate production wells may require larger equipment and longer well completion periods.

GHG reduction potential: Gas savings from avoiding flowback venting have been reported from 500 to 2000 MCF/day/well. Gas saved during green completions can be translated directly into methane emissions reductions based on the methane content of the produced gas. Amount of gas recovered can vary widely because it depends on a number of variables such as reservoir pressure, production rate, amount of other fluids (water, oil, solids, even and injected gases) lifted, and total completion time. EPA Natural Gas Star operators have reported that not all of the gas that is produced during well completions may be captured for sales [1]. Assessing the GHG reduction potential would be difficult to address in any meaningful way. We could make assumptions but there are many variables that go into the determination of the tonnes of CO2 including the methane content or the volume of gas vented during the well completion, the number of completions etc. This would be considered beyond the scope of our work on this topic paper as it would require substantial research to identify publicly available data.

Time to perform engineering and installation:	Transportation and set up of REC equipment takes approximately 1 day. However this is dependent on location. Some basins are quite vast and travel time is much higher. This can be mitigated by scheduling the equipment to follow the drilling equipment since presumably drilling scheduled to minimize travel/down time.
Typical scope of work description:	he decision process in planning an annual well completions program that includes REC technology consists primarily of four steps: 1. Examining the characteristics of the candidate wells that will be drilled during the year. Conventional wells that do not require hydraulic fracturing and well stimulation can be cleared of drilling fluids and connected to a sales line relatively quickly with minimal gas venting or flaring involved, therefore the use of REC technology for these applications is usually not economically justifiable. Wells that involve energized fracturing using inert gases require special considerations because the initial produced gas would not meet pipeline specifications due to the inert gas content. However, as the amount of inert gas decreases, the quality of the gas will likely meet pipeline specifications and may be economically worthwhile to capture through REC. 2. Determining the costs. The cost for green completions will depend on the need for special equipment (compressors, on-site dehydrators, membrane separator, etc.) which is tied to the characteristics of the well. Costs will also vary depending on whether operators choose to use third-party contractors to perform the RECs or whether operators choose to invest in their own portable REC equipment and operate it themselves. When using a third party to perform RECs, it is most cost effective to integrate the schedule of completions with the annual drilling program. To ensure profitability of using green

completion equipment, it is important for it to move efficiently from site to site within the field so that there is little down time when paying for equipment rental and labor.

3. Estimating savings. Savings will be dependent on the amount of gas recovered, the market price of natural gas and the amount of condensate that can be recovered in the REC three-phase separator. The amount of gas and condensate recovered will vary from well to well depending on the reservoir and operational characteristics of the drilling and completion.

4. Evaluating the economics of the completion program by weighing the economic benefits and expenses to determine whether this is a viable option. Regulatory considerations should also be made as green completions have been required in some areas.

Decision drivers

Technical:

Reservoir pressure: reservoir pressure must be higher than the back pressure in the REC or the gathering system. The maximum rated pressure of the system is dependent on the type of system and the individual vendor equipment. Based on one vendor (Weatherford) the maximum rated pressure would be depend upon the weakest link in the system components – which would be the process tank at 600 psi [12]. The maximum pressure of the sand trap for the Weatherford system is 10,000 psi. This information is specific to this system, and Vvendors should be contacted to verify individual applications prior to leasing or purchasing equipment. In low pressure reservoirs, RECs are often carried out with the aid of compressors for gas lift. Gas lift involves using gas from the sales line that is boosted with a compressor and routed down the well casing to push the frac fluids up the wellbore.

Compression to sales line: When the reservoir fluids have enough pressure to reach the wellhead but the gas recovered from the REC results in lower pressure than the sales line, a compressor engine may be required to boost flowback gas into the sales line. This technique is still experimental because of the difficulty operating a compressor on widely fluctuating flowback rate. Coal bed methane completion is an example where additional compression might be required

Inert gas stimulated wells: Some wells use inert gas (carbon dioxide and nitrogen) to energize the hydraulic fracturing process. The gas initially produced from these wells may have to be flared until the gas meets pipeline specifications. Alternatively, a portable acid gas membrane separator may be used to recover methane rich gas from the inert-heavy gas stream. As the flow rate of fluids drops and methane rich gas is encountered, backflow may be then switched over to the REC equipment so that the gas is captured.

Operational:

Connection to sales line: it is necessary that a piping system or gathering lines are in proximity to the well completion location so that captured gas during flowback can enter the sales line. This is why generally exploratory wells or delineation wells are not suitable for RECs since they are drilled in areas where there would not be a readily available pipeline system in place

Risk of blowouts: stable recovery of gas is essential. Green completions are not inherently suitable to violent releases of pressure such as blowouts. Pressure of the gas must not exceed the rating of the sand trap or separator vessels

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Summary

Analyst with research, data analysis, writing, and project management experience in the energy and environment field spanning the private, public, and non-profit sectors.

Education

2010-2012 **Harvard University John F. Kennedy School of Government** Cambridge, MA
Master in Public Policy, May 2012

- *Focus:* Energy and Environmental Policy, Quantitative Analysis.

2003-2007 **Haverford College** Haverford, PA
Bachelor of Arts, May 2007

- *Major*: History, *Minor*: Economics.

Professional Experience

2014-present **Clean Air Task Force** Menlo Park, CA
Senior Analyst, Super Pollutant Team

- Modeled the impact of state and federal oil and gas policies by creating a tool to track methane emissions under various policy scenarios.
- Conducted geospatial analysis using ArcGIS to assess flaring alternative technologies in North Dakota.
- Analyzed EPA data to quantify public health impacts of oil and gas development, including those from ozone formation and toxic air emissions.
- Presented results of analyses at industry and government conferences.
- Analyzed technical data on methane venting and flaring in the oil and gas industry for inclusion in state and federal regulatory comments.
- Managed projects from inception through completion with diverse project teams.
- Represented the organization in interviews with online, print, and radio reporters.

2012-2013 **Union of Concerned Scientists** Cambridge, MA
Energy Analyst, Climate and Energy Program

- Analyzed economics of coal plant retirements and risks of a reliance on natural gas electricity.
- Managed the production of reports, including collecting and analyzing data, writing and editing text, designing graphics, and working with the editor and designer.
- Collected and evaluated cost and performance data of energy projects to enable in-house modeling of energy and climate policies.
- Provided expertise on electricity and natural gas markets, electricity transmission and distribution, energy policy, and environmental impacts of energy sources.

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2011-2012 **Harvard University** Cambridge, MA
Belfer Center for Science and International Affairs
Research and Course Assistant, Cris Russell, Senior Fellow Environment & Natural Resources

- Helped develop a new course, "The Media, Energy & Environment: Global Policy & Politics": Conducted a literature review, developed a syllabus, organized logistics, and designed PowerPoint presentations for lectures.

2011 **U.S. Department of Energy** Washington, DC
Office of the Chief Financial Officer, Office of Risk Management
Program Analyst Intern

- Tracked budget and appropriations for multimillion-dollar Recovery Act projects.
- Wrote memos and fact sheets assessing and analyzing risks associated projects managed by the Office of Fossil Energy and the Office of Environmental Management.

2007- 2010 **MSCI Inc. (Formerly Riskmetrics Group and KLD Research & Analytics)** Boston, MA
Socially Responsible Investing Division
·**Senior Analyst and Sector Team Leader**: 2009-2010
·**Research Analyst II**: 2008-2009
·**Research Analyst I**: 2007-2008

- Supervised a team of five analysts researching the environmental, social, and governance performance of global basic materials companies.
- Worked collaboratively with members of the socially responsible investment and NGO community on issues relevant to energy and materials sectors.
- Analyzed the environmental, social, and governance performance of large-cap companies.
- Engaged in high-level dialogue with corporate social responsibility personnel from some of the largest companies in the sector.
- Worked with Sales, Marketing, and Product teams to create and manage new products.
- Managed the quality assurance processes for energy and materials sector research.
- Led Hiring Committee to recruit six new Research Analysts.

Technical Skills

- Microsoft Excel (incl. VBA/Macros)
- ArcGIS: Mapping and Spatial Analysis Software
- Tableau

Summary of Testimony of Lesley Fleishman, M.P.P.

Ms. Fleischman will provide a general description of data sources and methods, and will then describe specific analytical methods used for each of the tables presented, and implications.

General Data Sources and Methods:

She compiled a variety of tables and analyses based on publicly available data that industry has reported to the NM Oil Conservation Division. This includes the following:

C-115 Venting and Flaring Data by Operator accessed Nov. 2020
- http://www.emnrd.state.nm.us/OCD/documents/C-115Non-TransportedProductDispositionOperator20201112.xls

Statewide Natural Gas and Oil Production Summary by Month accessed Dec. 2020
- https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Reporting/Production/ProductionInjectionSummaryReport.aspx

Gas/Oil Production by Operator (2019, 2018, and 2017) accessed Sept. 2020
- http://www.emnrd.state.nm.us/OCD/documents/2019OperatorAnnualProductionReport.xlsx
- http://www.emnrd.state.nm.us/OCD/documents/2018OperatorAnnualProductionReport.xlsx
- http://www.emnrd.state.nm.us/OCD/documents/2017OperatorAnnualProductionReport.xlsx

C-115 Monthly Summary Report by Operator accessed Nov. 2020
- Download summary report for each operator: https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Reporting/Production/C115BalancingSummary.aspx

In cases where she reported data on production, venting, and flaring by operator, she combined data for operators sharing the same parent company (to the best of her knowledge). This includes:
- COG includes COG Operating LLC and COG Production, LLC
- XTO/Exxon includes XTO Energy, Inc, XTO Permian Operating LLC, BOPCO, L.P.
- Occidental includes Occidental Permian Lty, Oxy USA Inc, and Oxy USA WTP Limited Partnership
- Cimarex includes Cimarex Energy Co and Cimarex Energy Co. of Colorado
- Chevron includes CHEVRON U S A INC and CHEVRON MIDCONTINENT, L.P.

Specific Data and Implications

Table 1. Total Reported Venting and Flaring 2017-2019 (Thousand Cubic Feet (mcf))

(mcf)	2017	2018	2019	Percent change '17-'18	Percent change '18-'19
Flared	15,161,671	35,840,288	35,626,371	136%	-1%
Vented	2,016,186	784,782	853,209	-61%	9%
Vented +Flared	17,177,857	36,625,070	36,479,580	113%	0%

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- Data
  - Venting and Flaring from C-115 Venting and Flaring Data
  - Gas Production from Annual Production Reports
- Implications
  - Flaring more than doubled between 2017 and 2018 and stayed roughly constant between 2018 and 2019
  - While flaring decline slightly from 2018 to 2019, it was still enough to supply the home heating and cooking needs of 96% of New Mexico households for the year.[1]

Table 2: 2017-2019 Flaring by Top 25 Oil Producers, in Descending Order by 2019 Flaring Volume

	Oil produced (barrels)			Flared (mcf)		
Company	**2017**	**2018**	**2019**	**2017**	**2018**	**2019**
XTO Combined	6,996,173	11,480,489	21,175,868	625,818	5,081,880	4,467,296
DEVON ENERGY PRODUCTION COMPANY, LP	14,277,914	21,567,170	30,312,177	981,131	4,009,862	4,082,241
Ameredev Operating, Llc		331,310	1,400,859		1,793,187	3,591,068
Marathon Oil Permian Llc	1,356,663	5,630,590	6,606,003	1,098,142	2,929,539	2,252,093
Oxy USA/Occidental Permian	15,005,682	32,487,241	43,737,641	1,025,356	2,962,087	2,174,278
Cimarex Energy	8,469,203	11,300,063	12,537,851	832,567	2,223,657	2,062,078
COG Operating/COG Production	30,449,894	35,018,641	34,225,110	4,254,340	3,249,902	1,905,262
WPX Energy Permian, LLC	1,877,112	3,093,332	2,823,387	542,933	1,371,421	1,820,509
Eog Resources Inc	22,851,054	37,769,210	56,030,820	1,107,870	2,076,136	1,709,131
Matador Production Company	6,260,640	10,719,041	10,479,222	701,798	1,613,244	1,527,662
Centennial Resource Production, Llc	375,024	1,900,319	3,513,851	60,258	831,827	1,350,926
Tap Rock Operating, Llc	5,507	808,174	2,145,094			1,051,638
Bta Oil Producers, Llc	2,658,325	3,168,173	4,947,053	343,694	1,199,375	1,040,554
Apache Corporation	7,549,856	8,407,753	7,017,184	1,024,154	1,596,817	992,751
Spur Energy Partners LLC			1,045,617			891,471
Percussion Petroleum Operating, Llc	341,241	2,030,645	1,456,427		878,059	785,810
Chisholm Energy Operating, Llc	346,214	2,111,713	2,994,675			489,190
Conocophillips Company	4,397,092	3,967,516	3,753,413	522,547	513,205	331,961
Lime Rock Resources Ii-A, L.P.	1,069,286	1,318,333	955,160	132,138	191,616	85,508
Logos Operating, Llc	289,167	706,304	941,015	995	145,301	77,066
Advance Energy Partners Hat Mesa, Llc	93,818	964,944	2,685,487			47,339
Enduring Resources, Llc	3,134	3,179,099	3,966,870		44,699	37,208

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[1] 21 Natural Gas Consumption by End Use by State, U.S. Energy Information Administration. Available at https://www.eia.gov/dnav/ng/NG_CONS_SUM_A_EPG0_VRS_MMCF_A.htm.
Number of Natural Gas Customers by State, U.S. Energy Information Administration.
Available at https://www.eia.gov/dnav/ng/ng_cons_num_a_EPG0_VN3_Count_a.htm.

Chevron U S A Inc	7,386,903	7,274,617	9,555,530	32,715	50,932	27,114
Djr Operating, Llc	10,097	191,319	1,550,643		404	9,591
Mack Energy Corp	839,440	1,144,182	1,618,554	3,829	5,339	6,963

- Data
    - Flaring from C-115 Venting and Flaring Data
    - Oil Production from Annual Production Reports
    - Only includes companies with non-zero flaring. The following companies are among the top oil producers but reported no flaring in 2019.
        - Mewbourne Oil Co
        - Legacy Reserves Operating, LP
        - Kaiser-Francis Oil Co
        - Caza Operating, LLC
- Implications
    - While there is considerable variation in the amount of gas that different companies report that they flare, most of these top oil producers flare significant amounts of gas, while companies that primarily produce natural gas reported relatively little flaring.
    - Exxon, through its subsidiaries XTO and Bopco, tops the list, reporting that it flares 4.5 billion cubic feet (bcf) of gas in 2019. This would have provided the home heating and cooking needs of 71,600 New Mexican households for the year. Devon Energy reported that it flared 4.1 bcf and Ameredev reported that it flared 3.6 bcf. Three other top oil producers, Marathon, Oxy, and Cimarex, each reported that they flared over 2 bcf. An additional eight top oil producers reported that they flared more than 1 bcf of gas apiece.
    - The fact that there are major oil producers that have not reported any flaring highlights the need for strong enforcement of new reporting requirements in the proposed rule.

Table 3: Percent of Gas Production Flared by Top 25 Operators Reporting Flaring and Venting, Ranked By 2019 Percent of Production Flared or Vented

Company	Gas Produced (mcf)	Flared (mcf)	Vented (mcf)	Percent of Production flared or vented
Ameredev Operating, Llc	4,600,491	3,591,068		78%
Spur Energy Partners Llc	2,333,468	891,471		38%
Energen Resources Corporation	714,153		227,673	32%
Steward Energy Ii, Llc	645,320	203,494		32%
Impetro Operating Llc	808,641	244,726		30%
Percussion Petroleum Operating, Llc	2,950,123	785,810		27%
Centennial Resource Production, Llc	5,742,344	1,350,926		24%
Tap Rock Operating, Llc	6,050,693	1,051,638	73,000	19%
Wpx Energy Permian, Llc	15,706,022	1,820,509	236,807	13%

Murchison Oil And Gas, LLC	2,710,429	344,418		13%
Burnett Oil Co Inc	3,809,527	439,480		12%
Marathon Oil Permian Llc	27,338,268	2,252,093	28,794	8%
Fasken Oil & Ranch Ltd	1,770,362	124,446		7%
XTO Combined	72,028,232	4,467,296	429	6%
Chisholm Energy Operating, Llc	9,832,639	489,190		5%
Bta Oil Producers, Llc	25,363,851	1,040,554		4%
Matador Production Company	40,232,961	1,527,662		4%
Devon Energy Production Company, Lp	110,174,749	4,082,241		4%
Apache Corporation	31,669,356	992,751		3%
Cimarex Energy	78,995,491	2,062,078		3%
Conocophillips Company	16,091,164	331,961	1,506	2%
Legacy Reserves Operating, Lp	9,653,213		137,385	1%
Oxy Usa/Occidental Permian	155,501,254	2,174,278		1%
Cog Operating/Cog Production	151,328,114	1,905,262		1%
Eog Resources Inc	157,968,423	1,709,131		1%

- Data
  - Flaring from C-115 Venting and Flaring Data
  - Oil Production from Annual Production Reports
- Implications
  - Some major producers like OXY, COG, and EOG report that they flared a relatively small share of their overall gas production. Other major producers report that they flared significantly more gas. Exxon/XTO, Devon, Marathon, and WPX flared between 4% and 13% of total production. Still other major producers report that they flared extremely large shares of their gas production, led by Ameredev at a shocking 78%, Spur at 38%, Energen at 32%, Steward at 32%, Impetro at 30%, Percussion at 27%, and Centennial at 24%.

Table 4: 2019 Flaring by Top 20 Operators Reporting Flaring as a Percent of Total State Flaring

Company	Flared (mcf) 2019	Percent of total flaring reported statewide 2019	Percent of Production flared
XTO Combined	4,467,296	13%	6%
Devon Energy Production Company, Lp	4,082,241	12%	4%
Ameredev Operating, Llc	3,591,068	10%	78%
Marathon Oil Permian Llc	2,252,093	6%	8%
Oxy Usa/Occidental Permian	2,174,278	6%	1%
Cimarex Energy	2,062,078	6%	3%
Cog Operating/Cog Production	1,905,262	5%	1%
Wpx Energy Permian, Llc	1,820,509	5%	12%
Eog Resources Inc	1,709,131	5%	1%

Matador Production Company	1,527,662	4%	4%
Top 10	25,591,618	74%	
Centennial Resource Production, Llc	1,350,926	4%	24%
Tap Rock Operating, Llc	1,051,638	3%	17%
Bta Oil Producers, Llc	1,040,554	3%	4%
Apache Corporation	992,751	3%	3%
Spur Energy Partners Llc	891,471	3%	38%
Percussion Petroleum Operating, Llc	785,810	2%	27%
Chisholm Energy Operating, Llc	489,190	1%	5%
Burnett Oil Co Inc	439,480	1%	12%
Murchison Oil And Gas, LLC	344,418	1%	13%
Conocophillips Company	331,961	1%	2%
Top 20	33,309,817	96%	

- Data
    - Flaring from C-115 Venting and Flaring Data
- Implications
    - Just three companies, Exxon, Devon, and Ameredev, are responsible for over one-third of all reported flaring. The top 10 flaring companies account for 74%, and the top 20 account for 96% of all reported flaring statewide. This data indicates that flaring is concentrated in a handful of New Mexico oil and gas companies.
    - Some of the companies with the highest levels of flaring are flaring less than 2% of their produced gas. These companies may or may not have to reduce flaring, depending on how regulation is structured (i.e. 2% threshold, eliminate routine flaring, etc.) But, either way, this shows that getting to below 2% flaring is technically feasible.

Table 5a: Venting and Flaring by Operator with non-zero reported Venting and Flaring in Descending Order of Share of Company's Gas Production Vented or Flared, Jan-Aug 2019

Company	2019 (Jan-Aug) Gas Production (mcf)	2019 (Jan-Aug) Flared (mcf)	2019 (Jan-Aug) Vented (mcf)	2019 Percent of Production Flared and Vented
Joint Resources Company	4,294	4,294	-	100.0%
Bridgecreek Resources (Colorado), Llc	13,944	-	13,134	94.2%
Four Corners Exploration Co	991	-	828	83.6%
Ridgeway Arizona Oil Corp.	84,861	68,310	-	80.5%
Rock Creek Resources, Llc	5,061	-	3,587	70.9%
Ameredev Operating, Llc	2,452,400	1,684,607	-	68.7%
Manzano Llc	104,259	43,191	-	41.4%

Steward Energy Ii, Llc	381,736	138,088	-	36.2%
Energen Resources Corporation	610,686	-	197,569	32.4%
Percussion Petroleum Operating, Llc	2,950,123	785,810	-	26.6%
Dgp Energy, Llc	75,372	-	18,794	24.9%
Ascent Energy, Llc.	27,607	5,733	-	20.8%
Centennial Resource Production, Llc	3,972,132	771,847	-	19.4%
Wpx Energy Permian, Llc	10,948,613	1,609,730	157,334	16.1%
Spur Energy Partners Llc	797,273	123,834	-	15.5%
Impetro Operating Llc	604,882	89,307	-	14.8%
Strata Production Co	295,972	42,167	-	14.2%
Burnett Oil Co Inc	2,599,770	336,533	-	12.9%
Mcelvain Energy, Inc	272,609	34,582	421	12.8%
Tacitus, LLC	49,638	-	6,014	12.1%
Bopco, L.P.	9,257,749	1,073,289	-	11.6%
Tap Rock Operating, Llc	3,510,133	325,231	73,000	11.3%
Marathon Oil Permian Llc	20,447,314	2,285,919	27,791	11.3%
Pogo Oil & Gas Operating, Inc	687,429	66,930	-	9.7%
XTO Combined	33,482,335	2,756,766	14	8.2%
Read & Stevens Inc	781,598	52,432	-	6.7%
Murchison Oil And Gas, LLC	1,419,477	86,461	-	6.1%
Bta Oil Producers, Llc	16,213,321	700,497	-	4.3%
Devon Energy Production Company, Lp	76,703,510	3,150,276	-	4.1%
Matador Production Company	30,365,406	1,159,709	-	3.8%
Cimarex Comb	54,358,391	1,885,835	960	3.5%
Apache Corporation	23,119,428	787,162	-	3.4%
Mulloy Operating, Inc.	7,955	-	252	3.2%
Colgate Operating, Llc	495,194	15,417	-	3.1%
Fasken Oil & Ranch Ltd	1,201,812	31,601	-	2.6%
Chisholm Energy Operating, Llc	6,606,718	169,009	-	2.6%
Conocophillips Company	10,709,944	245,029	1,506	2.3%
Special Energy Corp	730,172	14,475	-	2.0%
Legacy Reserves Operating, Lp	5,832,432	-	115,207	2.0%
Lime Rock Resources Ii-A, L.P.	2,898,096	49,333	-	1.7%
Eog Resources Inc	100,044,382	1,272,506	-	1.3%
COG Comb	109,614,407	1,321,036	-	1.2%
Cml Exploration, Llc	193,520	-	2,128	1.1%
Oxy Comb	148,688,416	1,603,741	-	1.1%
Grizzly Operating, Llc	4,422,901	-	28,386	0.6%
Marshall & Winston Inc	465,995	2,646	-	0.6%
Logos Operating, Llc	22,537,180	69,661	8,657	0.3%
Mack Energy Corp	1,846,750	6,118	-	0.3%

Enduring Resources, Llc	19,486,116	37,124	-	0.2%
Chevron U S A Inc	51,965,178	22,060	10,815	0.1%
Dugan Production Corp	5,479,247	-	1,074	0.0%
Caza Operating, Llc	2,835,844	-	379	0.0%
Mewbourne Oil Co	57,567,363	-	3,491	0.0%
Bp America Production Company	56,384,915	-	1,521	0.0%
Hilcorp Energy Company	225,201,074	-	2,473	0.0%

- Data
    - Only data for January through August, so we can see an apples to apples comparison with 2020 data (presented below)
    - Jan-Aug data is taken from the C-115 Monthly Summary Report by Operator.
    - Venting and Flaring from C-115 Venting and Flaring Data
    - Only showing companies that report a non-zero amount of venting or flaring
- Implications
    - In 2019 (Jan-Aug), 27 companies vented or flared more than 5% of their gas production, and 37 companies vented or flared more than 2% of their gas production.
    - Note: This table only shows companies that report non-zero amounts of venting or flaring

Table 5b: Venting and Flaring by Operator with non-zero reported Venting and Flaring, in descending order of share of Company's Gas Production Vented or Flared, Jan-Aug 2020

Company	2020 (Jan-Aug) Gas Production (mcf)	2020 (Jan-Aug) Flared (mcf)	2020 (Jan-Aug) Vented (mcf)	2020 Percent of Production Flared and Vented
D.W.R. Oil Properties, Inc.	5,595	5,595	-	100.0%
Tamaroa Operating, Llc	19,380	19,380	-	100.0%
Bridgecreek Resources (Colorado), Llc	12,891	14	12,043	93.5%
Ridgeway Arizona Oil Corp.	103,183	90,246	-	87.5%
Four Corners Exploration Co	1,806	-	1,267	70.2%
Impetro Operating Llc	501,108	334,285	-	66.7%
Lh Operating, Llc	37,821	24,317	-	64.3%
Manzano Llc	239,262	134,071	-	56.0%
Ameredev Operating, Llc	3,314,288	1,287,550	-	38.8%
Special Energy Corp	17,529	5,291	-	30.2%
Ascent Energy, Llc.	196,326	56,670	-	28.9%
Murchison Oil And Gas, LLC	2,528,032	593,305	-	23.5%
Lime Rock Resources Ii-A, L.P.	2,713,603	590,673	-	21.8%

Centennial Resource Production, Llc	6,648,088	1,361,497	-	20.5%
Mulloy Operating, Inc.	36,876	4,405	201	12.5%
Prima Exploration, Inc.	161,396	11,872	8,011	12.3%
Tap Rock Operating, Llc	7,554,538	852,715	-	11.3%
Spur Energy Partners Llc	18,236,472	1,727,059	-	9.5%
Energen Resources Corporation	37,821	-	3,321	8.8%
Steward Energy Ii, Llc	428,430	37,583	-	8.8%
Strata Production Co	295,972	25,110	-	8.5%
Chisholm Energy Operating, Llc	7,135,965	549,678	-	7.7%
Burnett Oil Co Inc	2,306,766	171,614	-	7.4%
Advance Energy Partners Hat Mesa, Llc	3,788,899	189,794	-	5.0%
Read & Stevens Inc	781,598	37,493	-	4.8%
Wpx Energy Permian, Llc	8,833,331	260,135	156,073	4.7%
Marathon Oil Permian Llc	19,750,245	812,724	5,635	4.1%
Catena Resources Operating, Llc	374,075	12,123	-	3.2%
Matador Production Company	31,340,045	965,426	-	3.1%
Conocophillips Company	10,501,927	241,625	-	2.3%
Bta Oil Producers, Llc	17,496,375	344,372	-	2.0%
XTO Combined	73,449,126	1,307,012	2,630	1.8%
Tacitus, LLC	115,898	-	1,791	1.5%
COG Comb	113,365,138	1,696,776	-	1.5%
Cimarex Comb	47,270,250	555,956	-	1.2%
Cml Exploration, Llc	166,535	560	1,323	1.1%
Apache Corporation	25,188,538	253,394	-	1.0%
Marshall & Winston Inc	271,219	2,301	-	0.8%
Devon Energy Production Company, Lp	116,746,505	713,060	-	0.6%
Legacy Reserves Operating, Lp	5,832,432	-	29,228	0.5%
Eog Resources Inc	111,910,019	428,480	-	0.4%
Colgate Operating, Llc	399,850	1,459	-	0.4%
Fasken Oil & Ranch Ltd	1,102,810	3,023	-	0.3%
Mack Energy Corp	1,846,750	4,565	-	0.2%
Grizzly Operating, Llc	3,080,842	-	4,469	0.1%
Dugan Production Corp	5,320,410	-	3,008	0.1%
Logos Operating, Llc	20,112,854	-	10,026	0.0%
Chevron U S A Inc	66,751,755	18,206	7,493	0.0%
Oxy Comb	164,324,037	8,500	21,947	0.0%
Mewbourne Oil Co	67,996,351	-	6,464	0.0%
Bp America Production Company	35,467,471	-	412	0.0%
Hilcorp Energy Company	216,817,908	-	296	0.0%

- Data
    - Only data for January through August, because data is not complete for 2020.
    - Jan-Aug data is taken from the C-115 Monthly Summary Report by Operator.
    - Venting and Flaring from C-115 Venting and Flaring Data
    - Only showing companies that report a non-zero amount of venting or flaring
- Implications
    - In 2020 (Jan-Aug), 24 companies vented or flared more than 5% of their gas production, and 30 companies vented or flared more than 2% of their gas production.
    - The following companies reported that they flared greater than 2% of their gas in 2019 (Jan-Aug), but below 2% in 2020 (Jan-Aug):
        - ROCK CREEK RESOURCES, LLC
        - DGP ENERGY, LLC
        - Tacitus, LLC
        - XTO comb
        - BTA OIL PRODUCERS, LLC
        - DEVON ENERGY PRODUCTION COMPANY, LP
        - Cimarex comb
        - APACHE CORPORATION
        - COLGATE OPERATING, LLC
        - FASKEN OIL & RANCH LTD
    - The following companies reported that they flared less than 2% of their gas in 2019 (Jan-Aug), but above 2% in 2020 (Jan-Aug)
        - D.W.R. OIL PROPERTIES, INC.
        - Tamaroa Operating, LLC
        - LH Operating, LLC
        - SPECIAL ENERGY CORP
        - LIME ROCK RESOURCES II-A, L.P.
        - Prima Exploration, Inc.
        - ADVANCE ENERGY PARTNERS HAT MESA, LLC
        - Catena Resources Operating, LLC
    - Note: This table only shows companies that report non-zero amounts of venting or flaring

THOMAS O. SINGER, Ph.D.

singer@westernlaw.org

EDUCATION

Harvard University
Special Studies: Resources and Development
A.B., 1974 (Magna cum laude with highest honors)

Stanford University
Stanford Graduate School of Business, Public Management Program
MBA, 1977

The George Washington University
School of Government and Business Administration
Ph.D., International Business, 1990

PROFESSIONAL EXPERIENCE

Western Environmental Law Center
July 2012 – present
Senior Policy Advisor
The main focus of my work at WELC is advocacy and litigation support to limit the environmental impacts of oil and natural gas development on federal lands, in particular the release of methane, a potent greenhouse gas. WELC is leading a national stakeholder group working to update the Bureau of Land Management's rule on oil and gas methane waste. I also work with local place-based groups to challenge BLM Field Office resource management plans and oil and gas lease sales. In the clean energy area, I am engaged in negotiations and litigation in NM Public Regulation Commission cases regarding resource planning and clean replacement power for PNM's coal unit retirements at the San Juan Generating Station.

Natural Resources Defense Council
March 2004 – July 2012
Senior Advocate
The focus of my work at NRDC was research and advocacy for climate and clean energy policies in New Mexico. I was engaged in the development of the first NM greenhouse gas inventory and in the Environmental Improvement Board's adoption of a NM oil and gas GHG reporting rule. I also researched and co-authored a major NRDC report on measures to reduce methane waste in oil and gas production. For the Western Climate Initiative I led a group of advocates in securing a strong model state oil and gas GHG reporting rule. In 2005 I was appointed by Gov. Richardson to Chair his Energy Efficiency Task Force, and worked successfully on passage and implementation of laws establishing a renewable energy portfolio standard and an energy efficiency resource standard. I served as an expert witness in several NM PRC cases and participated in several rule makings, and worked extensively with other state environmental advocacy groups and with New Mexico's Congressional delegation.

CA
Ex. 17

Outdoor Family, Inc.
October 1999 - 2004
Vice-President and Co-Founder
Started and built internet manufacturing and retail company specializing in outdoor gear for kids. I was responsible for all aspects of business including marketing, production, finance, and operations.

Western Governors' Association
September 1991- April 1999
Director of Research
Managed WGA research projects and staff as well as field projects and demonstrations. In addition to regular short-term research requests from governors, major multi-year projects and their key sponsors included:

- **Healthcare:** Health Passport (smart card-based portable medical record demonstration)/Federal public health agencies
- **Public Health:** Western Electronic Benefits Alliance (card-based delivery of WIC, food stamps, and other Federal cash assistance programs)/Federal welfare agencies
- **Education:** Western Governors' University (multi-state consortium for internet-based higher education)/ Alfred P. Sloan Foundation
- **Agriculture:** Open Lands Project (collaboration with American Farmland Trust and The Trust for Public Land to promote new tools for conservation on private lands in the West)/David and Lucile Packard Foundation
- **Economic development:** DOIT Project (accelerated commercialization of cleanup technologies for Federal facilities)/U.S. Department of Energy
- **International affairs:** U.S.-Mexico border environmental cooperation/Ford & Charles Stewart Mott Foundations; and International Trade Agreements and the States (research to support governors' positions on the environmental impacts of US trade policy, publication in peer review journals)/William and Flora Hewlett Foundation
- **Information technology:** SmartStates (multi-state development of e-commerce applications for state agencies) /internal WGA funding

The American University
September 1990-August 1991
Visiting Assistant Professor of International Business
Taught graduate international finance and international banking courses and undergraduate international business fundamentals course.

The Urban Institute
1987-1990
Research Associate
Conducted research on program evaluation of state international business programs and developed a national manual for performance monitoring in economic development.

The George Washington University
1986-1989
Adjunct Professor, School of Government and Business Administration
Taught undergraduate international business fundamentals courses.

Overseas Private Investment Corporation, Finance Department
January-September 1985
Financial Analyst/Intern
Assisted in project finance for U.S private direct investment in developing countries. Conducted market research, financial analysis and forecasting, and country risk analysis.

Department of Transportation and Public Facilities, State of Alaska
February-August 1983
Special Assistant to the Commissioner
Conducted policy analysis on energy facility financing and management of the Alaska Power Authority.

T. Singer and Associates, Juneau, Alaska
June 1982-February 1983
Independent Consultant
Conducted policy analysis on economic impact of state expenditures, import substitution and structural change, impact of proposed gas pipeline, and economics of export of Alaskan oil to Japan.

Office of the Governor, State of Alaska
October 1978-December 1981
Policy Analyst
Conducted policy analysis on establishment of the Alaska Permanent Fund, development finance and energy facilities financing.

Alaska State Legislature
House Special Committee on the Permanent Fund, and Subcommittee on the Renewable Resources Development Fund
June 1977-June 1978
Assistant to Committee Co-Chairmen
Conducted committee work and research supporting creation of the Alaska Permanent Fund and the Alaska Renewable Resources Corp.

Harvard University, Graduate School of Design
September 1974-June 1975
Lecturer
Taught Freshman Seminar on "Land Use and Natural Resources"

PUBLICATIONS AND PRESENTATIONS

Harvey, Susan, Vignesh Gowrishankar and Thomas O. Singer. March 2012. “Leaking Profits: How the U.S. oil and gas Industry can reduce pollution, conserve resources, and make money by preventing methane waste.” Natural Resources Defense Council. New York, NY.

Singer, Thomas O. and Robert Stumberg. 1999. “A Multilateral Agreement on Investment: Would It Undermine Subnational Environmental Protection?” The Journal of Environment and Development, V8n1 (March).

Orbuch, Paul M. and Singer, Thomas O. 1995. “International Trade, the Environment, and the States: An Evolving State-Federal Relationship.” The Journal of Environment and Development. Summer, 1995.

Orbuch, Paul M. and Singer, Thomas O. 1994. "International Trade, the Environment, and the States: An Evolving State-Federal Relationship." Paper presented at the Association for Public Policy and Management (APPAM) 1994 Annual Research Conference, Chicago, Illinois, October 29, 1994.

Singer, Thomas O. and Michael R. Czinkota. 1994. "Factors Associated with Effective Use of Export Assistance". Journal of International Marketing. 2(1), 53-71.

Singer, Thomas. "Regional Mechanisms for Border Environmental Governance." Address to a Conference on the U.S.-Mexico Border: An International Region Under Stress sponsored by the Udall Center for Studies in Public Policy, University of Arizona and the International Transboundary Resources Center, University of New Mexico Law School, Santa Fe, New Mexico, November 20-21, 1993.

Singer, Thomas. "Environmental Planning for the U.S.-Mexico Border Region." Address to the XII Border Governors' Conference, Ecology and Environment Committee, Monterrey, Mexico, March 1993.

Schaefer, Matt, and Singer, Thomas. 1992. "Multilateral Trade Agreements and U.S. States: An Analysis of Potential GATT Uruguay Round Agreements." Journal of World Trade 26(6), 31-59.

Schaefer, Matt and Singer, Thomas. "Multilateral Trade Agreements and U.S. States: An Analysis of Potential GATT Uruguay Round Agreements." Paper presented at the Association for Public Policy and Management (APPAM) 1992 Annual Research Conference, Denver, Colorado, October 31, 1992.

Santillanez, Elizabeth, and Singer, Thomas. 1992. "Mexico's New Environmental Responsibilities and the Role of Environmental Federalism." Paper presented at the 6th Annual Symposium on Hispanic Issues, Boulder, Colorado, October 8.

Singer, Thomas. "Regional Mechanisms for Border Environmental Governance." Address to a Conference on the U.S.-Mexico Border: An International Region Under Stress sponsored by the Udall Center for Studies in Public Policy, University of Arizona and the International Transboundary Resources Center, University of New Mexico Law School, Santa Fe, New Mexico, November 20-21, 1993.

Singer, Thomas. "Environmental Planning for the U.S.-Mexico Border Region." Address to the XII Border Governors' Conference, Ecology and Environment Committee, Monterrey, Mexico, March 1993.

Singer, Thomas O. and Michael R. Czinkota. 1991. "Factors Associated with Effective Use of Export Assistance." Paper presented at the Annual Meeting of the Academy of International Business, Miami, Florida, October 18.

Thomas O. Singer, with Harry P. Hatry, Mark Fall, and Blaine E. Liner. 1991. "Evaluating Nonfinancial Business Assistance Programs." In Local Economic Development - Strategies for a Changing Economy, R. Scott Fosler, Ed. Washington, D.C.: ICMA

Hatry, Harry P., Mark Fall, Thomas O. Singer and Blaine E. Liner. 1990. Monitoring the Outcomes of Economic Development Programs. Washington, D.C.: The Urban Institute Press.

Tussing, Arlon, Lee Huskey, and Thomas O. Singer. 1983. The Place of Support- Sector Growth, Import Substitution, and Structural Change in Alaska's Economic Development. Institute of Social and Economic Research, Anchorage, Alaska.

OCD Proposed Methane Waste Rule
Testimony of Thomas O. Singer, Ph.D.
OCC Hearing Jan. 4, 2021

Western
Environmental
Law Center

CA
Ex. 18

NMOGA *Flaring in the Oilfield* Report
Reasons Operators Flare

1. Emergencies, upset conditions, and other safety
2. Scheduled and unscheduled maintenance
3. Drilling completion and flowback
4. Production testing
5. Inadequate wellbore pressure/inadequate compression
6. Temporary infrastructure capacity constraints

District I
1625 N. French Dr., Hobbs, NM 88240
District II
1301 W. Grand Avenue, Artesia, NM 88210
District III
1000 Rio Brazos Road, Aztec, NM 87410
District IV
1220 S. St. Francis Dr., Santa Fe, NM 87505

HOBBS OCD
APR 06 2015
RECEIVED

State of New Mexico
Energy Minerals and Natural Resources
Oil Conservation Division
1220 South St. Francis Dr.
Santa Fe, NM 87505

Form C-129
Revised August 1, 2011

Submit one copy to appropriate District Office

NFO Permit No. ____________
(For Division Use Only)

APPLICATION FOR EXCEPTION TO NO-FLARE RULE 19.15.18.12

(See Rule 19.15.18.12 NMAC and Rule 19.15.7.37 NMAC)

A. Applicant **XTO ENERGY INC.**

whose address is **200 N. LORAINE, STE. 800 MIDLAND, TX 79701**

hereby requests an exception to Rule 19.15.18.12 for **30** days or until

April 30, Yr **15**, for the following described tank battery (or LACT):

Name of Lease **Mis Amigos** Name of Pool **Triple X; Bone Spring, West**

Location of Battery: Unit Letter **O** Section **31** Township **23S** Range **33E**

Number of wells producing into battery **4** 30-025-41003 30-025-40590

B. Based upon oil production of **800** barrels per day, the estimated * volume

of gas to be flared is **24350** MCF; Value **450** per day.

C. Name and location of nearest gas gathering facility:

DCP Midstream

D. Distance ____________ Estimated cost of connection ____________

E. This exception is requested for the following reasons: **DCP high line pressures and new drilled wells causing us to max out our compressors and sending gas to flare INTERMITTENTLY.**

OPERATOR	OIL CONSERVATION DIVISION
I hereby certify that the rules and regulations of the Oil Conservation Division have been complied with and that the information given above is true and complete to the best of my knowledge and belief.	Approved Until 4/30/2015
Signature Patty Urias	By Maxey G Brown
Printed Name & Title **Patty Urias, Regulatory Analyst**	Title Dist Supervisor
E-mail Address **patty_urias@xtoenergy.com**	Date 4/6/2015
Date **4/2/2015** Telephone No. **432.620.4318**	

* Gas-Oil ratio test may be required to verify estimated gas volume.

APR 07 2015

Western Environmental Law Center
westernlaw.org

Well Details

API: 30-025-41003

Well Name: MIS AMIGOS STATE #002H

Operator: XTO ENERGY, INC

Pools: [96674] TRIPLE X;BONE SPRING, WEST

ULSTR: P-31-23S-33E

Footages: 330 FSL & 660 FEL

County: Lea

District: Hobbs

***Note:** If you are using Microsoft Internet Explorer and your system does not allow you to open TIFF images from the Internet without saving them first, please contact your administrator.*

Sort Order: ● Ascending ○ Descending


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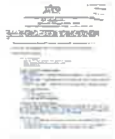
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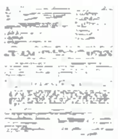
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(135 kB - 4/14/2014)


(64 kB - 4/7/2015)


(43 kB - 10/8/2015)


(625 kB - 4/4/2016)


(1914 kB - 4/4/2016)


(631 kB - 7/11/2016)


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(635 kB - 2/6/2017)


(611 kB - 4/6/2017)


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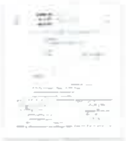
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(58 kB - 6/15/2018)


(62 kB - 7/25/2018)


(65 kB - 10/25/2018)


(64 kB - 2/6/2019)


(54 kB - 7/1/2019)


(328 kB - 4/2/2020)


(328 kB - 4/9/2020)


(418 kB - 7/2/2020)


(450 kB - 10/1/2020)

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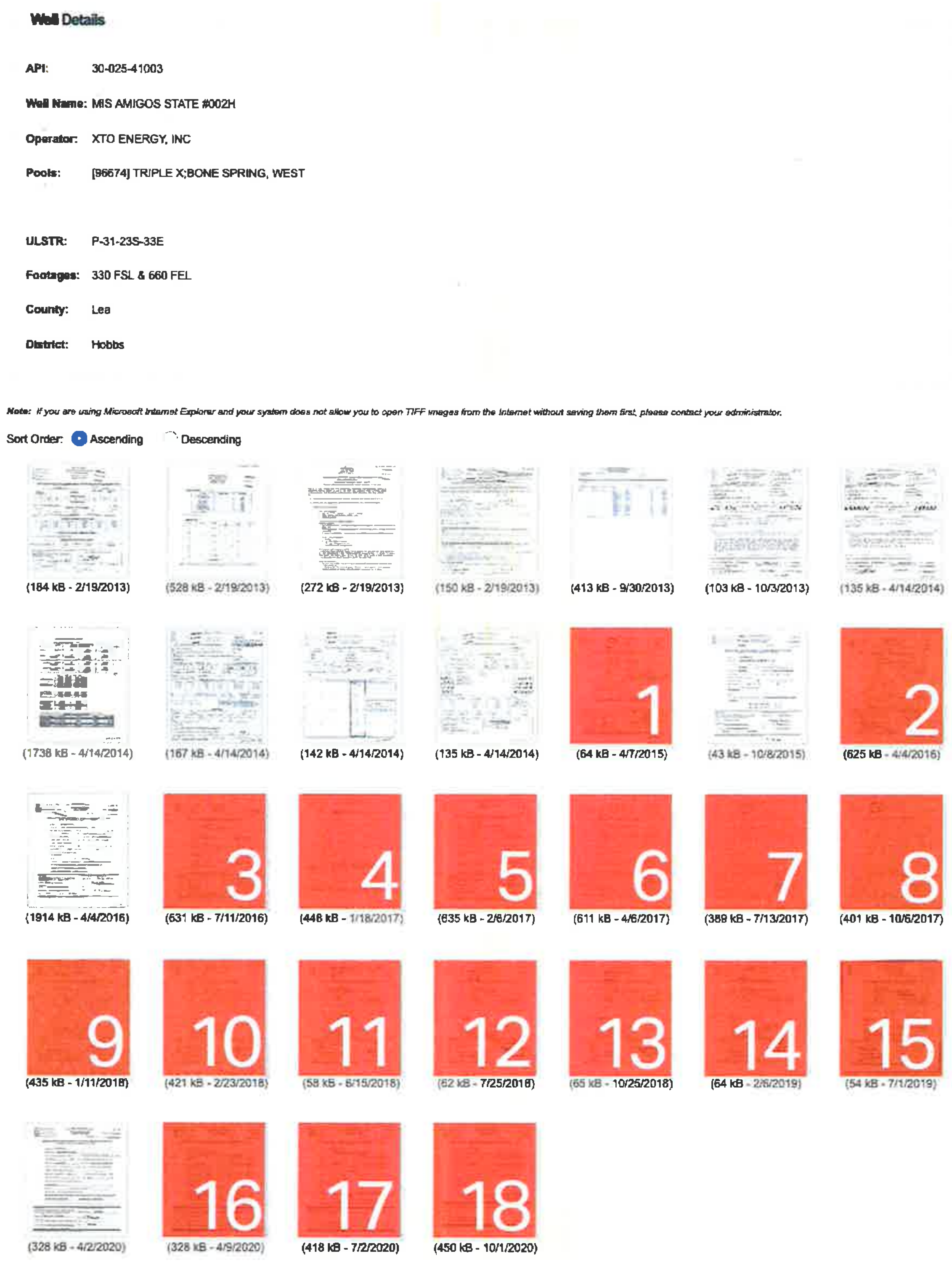

Well Details

API: 30-025-41003

Well Name: MIS AMIGOS STATE #002H

Operator: XTO ENERGY, INC

Pools: [96674] TRIPLE X;BONE SPRING, WEST

ULSTR: P-31-23S-33E

Footages: 330 FSL & 660 FEL

County: Lea

District: Hobbs

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(135 kB - 4/14/2014)

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(142 kB - 4/14/2014)
(135 kB - 4/14/2014)
(64 kB - 4/7/2015)
(43 kB - 10/8/2015)
(625 kB - 4/4/2016)

(1914 kB - 4/4/2016)
(631 kB - 7/11/2016)
(446 kB - 1/18/2017)
(635 kB - 2/6/2017)
(611 kB - 4/6/2017)
(389 kB - 7/13/2017)
(401 kB - 10/6/2017)

(435 kB - 1/11/2018)
(421 kB - 2/23/2018)
(58 kB - 6/15/2018)
(62 kB - 7/25/2018)
(65 kB - 10/25/2018)
(64 kB - 2/6/2019)
(54 kB - 7/1/2019)

(328 kB - 4/2/2020)
(328 kB - 4/9/2020)
(418 kB - 7/2/2020)
(450 kB - 10/1/2020)

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westernlaw.org

Routine Flaring at New Mexico Oil Wells

COMPANY	WELL API NUMBER	FIRST APPLICATION DATE	LAST APPLICATION DATE	TOTAL NUMBER OF APPLICATIONS	TIME PERIOD FLARING APPROVED	REASONS GIVEN
XTO	30-025-41003 30-025-40590 30-025-41002 30-025-40591	April 6, 2015	Oct. 1, 2020	18	4 years 1 month	Midstream compressor issues Third party pipeline constraints
EOG	30-025-41546 30-025-41907	August 8, 2015	Dec. 11, 2020	21	4 years 8 months	Third party compressor trouble Midstream volatility
COG	30-025-40688 30-025-42742	February 25, 2016	Oct. 28, 2020	16	3 years 11 months	Line pressure issues Unplanned midstream curtailment
Matador	30-025-44013 30-025-41841 30-025-45223 30-025-44361 30-025-44649 30-025-45760	March 15, 2018	Nov. 23, 2020	15	2 years 8 months	Gas plant issues Pipeline issues
Marathon	30-025-44165	March 3, 2019	Dec. 16, 2020	8	1 year 10 months	Gas plant problems High sales line pressure

Source: Inspection of public records request, OCD response: well files, C129 records for March and Sept. 2019
Note: Each of the wells shown is not included in every application by the producer, but most wells are included in most applications. In most cases, applications and approvals run continuously during the periods shown.

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From:

Tackling Flaring: Learnings from Leading Permian Operators

Gaffney Cline

> “Each producer we spoke to attributes their top-tier performance with the strategic decision to require a gas line be connected on all new wells, eliminating the need to flare associated gas in the first place. Thus, each producer mandates that infrastructure takeaway be in place before a well comes online. This is coupled with the willingness to shut in wells if the infrastructure is not in place.”

From:

Tackling Flaring: Learnings from Leading Permian Operators

Gaffney Cline

> "Interestingly, these producers don't consider the lack of takeaway as a barrier but a constraint, i.e., a condition that needs to happen before a project is successful. One producer offered an insightful analogy: Just as permitting is built into the process as an additional constraint, meaning a producer would not drill a well without a permit, a producer should not drill a well without takeaway."

From:

Tackling Flaring: Learnings from Leading Permian Operators

Gaffney Cline

"Another important point is that necessity of takeaway is in no way an unexpected event. It takes planning, communication, and coordination, which implies the need for time. However, producers suggested there is plenty of time, usually years in advance, considering the months it takes to create a production schedule and budget, construct a pad, and then drill and complete the well."

From:

Tackling Flaring: Learnings from Leading Permian Operators

Gaffney Cline

> “Although the terms of these [takeaway] contracts are confidential, producers shared with us that they provide timing and location of well development and projected production volumes well enough in advance to enable midstream companies to respond with adequate gathering and processing capacity. In the spirit of partnership, midstream companies share existing and planned future capacity additions and constraints to better align drilling schedules.”

Dallas Fed Energy Survey, Second Quarter 2020

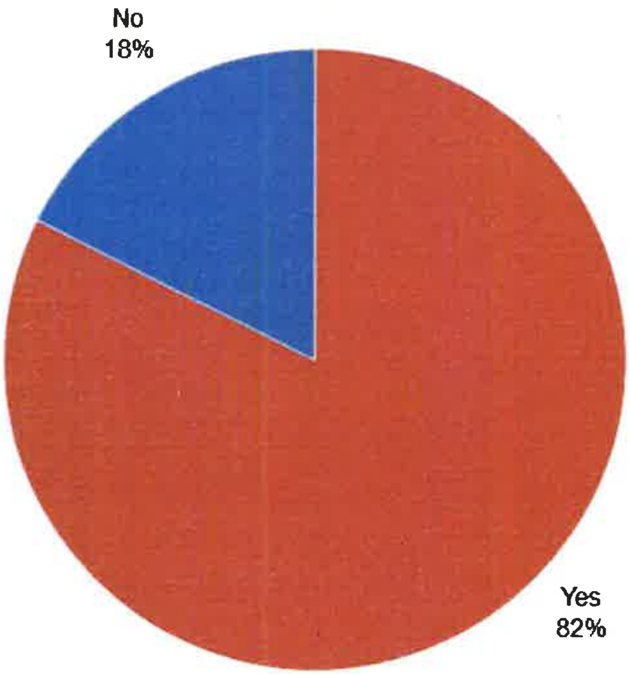
Special Questions

Data were collected June 10–18; 165 oil and gas firms responded to the special questions survey.

Exploration and Production (E&P) Firms

Did your firm shut in or curtail any production in the second quarter?

Eighty-two percent of E&P executives said their firm shut in or curtailed production in the second quarter. The remaining 18 percent did not shut in or curtail production.

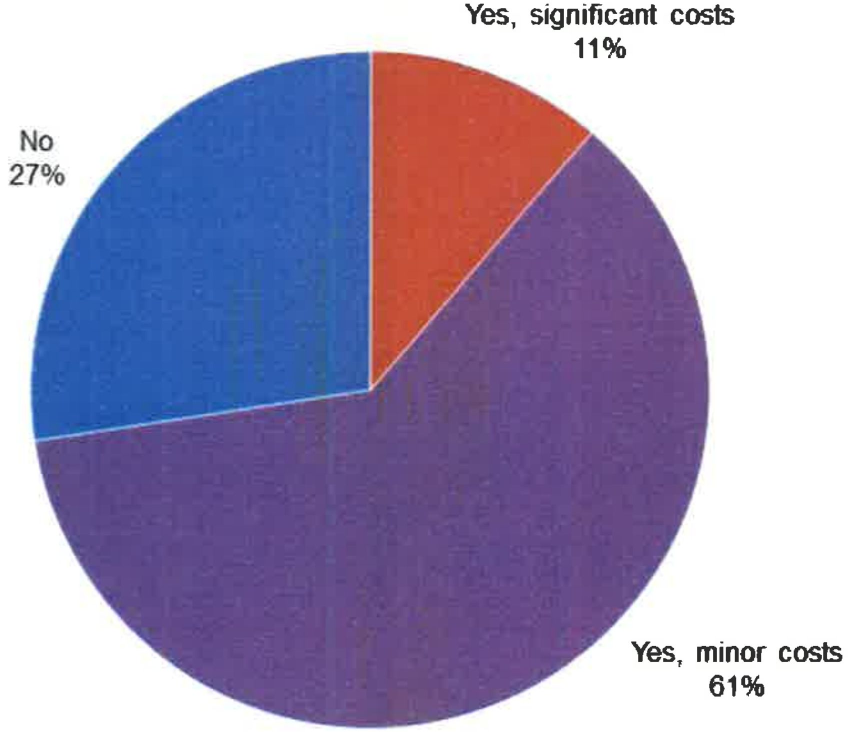


NOTE: Executives from 108 exploration and production firms answered this question during the survey collection period, June 10–18, 2020.
SOURCE: Federal Reserve Bank of Dallas.

Dallas Fed Energy Survey, Second Quarter 2020

Do you expect extra costs when putting the wells back online?

This question was only posed to E&P executives whose firms still have production shut in and/or curtailed. More than half of executives—61 percent—expect minor costs when placing shut-in and/or curtailed wells back online. Twenty-seven percent anticipate no costs, while 11 percent expect significant costs. *(Percentages don't sum to 100 due to rounding.)*



NOTES: Executives from 62 exploration and production firms answered this question during the survey collection period, June 10–18, 2020. Percentages don't sum to 100 due to rounding. This question was only posed to executives who indicated that their firm currently has any oil production shut in or curtailed.
SOURCE: Federal Reserve Bank of Dallas.

California Accredited Verification Bodies

The following verification bodies are accredited to perform verification services for greenhouse gas emissions data reports.

Individual Verifiers & Executive Orders

Executive Order	Verification Body	Contact Information	Accreditations*
H-19-001 Accredited in 2015 Valid through 3/11/22	**Adelante Consulting, Inc.** 430 W. Highway 6, Los Lunas, NM 87031	Virginia Smith 505-920-4150 vsmith@adelanteconsulting.com www.adelanteconsulting.com	# of Verifiers: 2 Transactions: - Oil and Gas: - Process: -
H-19-002 Accredited in 2009 Valid through 3/11/22	**Analytical Environmental Services** 1801 7th Street, Suite 100 Sacramento CA 95811	Trent Wilson 916-447-3479 twilson@analyticalcorp.com www.analyticalcorp.com	# of Verifiers: 3 Transactions: 2 Oil and Gas: - Process: -
H-19-003 Accredited in 2010 Valid through 3/11/22	**Ashworth Leininger Group** 601 East Daily Drive, Suite 302 Camarillo CA 93010	Michael Waller 805-764-6003 mwaller@algcorp.com www.algcorp.com	# of Verifiers: 6 Transactions: 6 Oil and Gas: 5 Process: 3
H-19-004 Accredited in 2010 Valid through 3/11/22	**ATC Group Services** 1117 Lone Palm Avenue, Suite B Modesto CA 95351	Mike Sonke 209-579-2221 mike.sonke@atcags.com www.atcgroupservices.com	# of Verifiers: 3 Transactions: 1 Oil and Gas: 1 Process: 1
H-20-022 Accredited in 2010 Valid through 3/17/23	**Apex Cos, LLC.** 15850 Crabbs Branch Way, Suite 200 Rockville. MD 20855	Trevor Donaghu 925-281-1760 trevor.donaghu@apexcos.com	# of Verifiers: 2 Transactions: 1 Oil and Gas: 1

Western
Environmental
Law Center

CHARLES de SAILLAN

25 Wildflower Way
Santa Fe, New Mexico 87506
(505) 819-9058 (Mobile)
(505) 820-1531 (Home)

EXPERIENCE

June 2018 to present

NEW MEXICO ENVIRONMENTAL LAW CENTER
Santa Fe, New Mexico

Staff Attorney
Represented ranching and ecotourism businesses in opposing permits for the Copper Flat Mine under the N.M. Water Quality Act and the N.M. Mining Act, including administrative hearings, appeal to the N.M. Water Quality Control Commission, and appeal to the N.M. Court of Appeals; represented community organizations and State legislators in action against the U.S. Air Force seeking injunctive relief for cleanup of bulk fuel spill at Kirtland Air Force Base; represented community organizations and acequia association in action against U.S. Environmental Protection Agency challenging 2020 rulemaking on "waters of the United States" under the Clean Water Act; represented community organizations in groundwater discharge permit proceedings for Los Alamos National Laboratory remediation; drafted and promoted legislation on various environmental issues including citizen suits under environmental laws, emissions of greenhouse gases, and the scope of groundwater protection; member of the Governor's Methane Advisory Panel that made recommendations on regulation of methane emissions from oil and gas production; represented State organization in advocating for funding for electric school buses under the Volkswagen settlement.

January 2014
to May 2018

NEW MEXICO INTERSTATE STREAM COMMISSION
Legal Bureau
Santa Fe, New Mexico

Attorney
Represented the Commission in administrative and civil litigation and advised the Commission on matters involving compliance with interstate river compacts, transfer of water rights, and protection of endangered aquatic and riparian species; drafted and negotiated funding agreements to implement the Taos Pueblo Indian water rights settlement; managed the N.M. Strategic Water Reserve; co-authored a report (in draft) on the effects of climate change on water resources in the Pecos River Basin.

December 1999
to December
2013

NEW MEXICO ENVIRONMENT DEPARTMENT
Office of General Counsel
Santa Fe, New Mexico

Assistant General Counsel
Represented the Department in enforcement and permitting actions under State environmental laws: served as lead Department counsel in administrative adjudicatory hearings on the hazardous waste permit for Los Alamos National Laboratory under the N.M. Hazardous Waste Act, and the groundwater discharge permits for the Molycorp, Chino, and Tyrone mines under the N.M. Water Quality Act; briefed and argued the Tyrone appeal before the N.M. Court of Appeals; briefed and
designation of outstanding national resource waters before the N.

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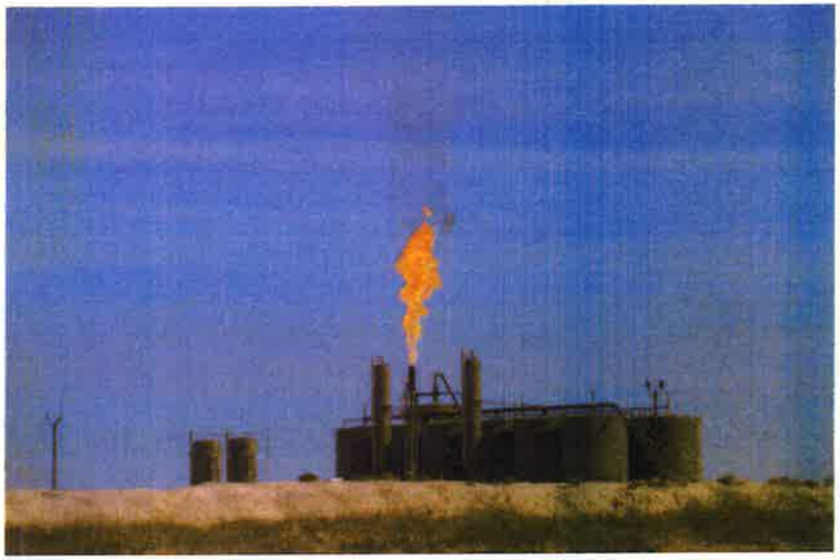
Ex. 19



Thank you!

Nathalie Eddy, Field Advocate, CO & NM
neddy@earthworks.org
Tel: 720 935-7404

Adella Begaye, BSN, RN, PHN
Retired
0-5, CDR
CV November 2020

Performance

Accomplishments:

- Volunteered for COVID-19 response as a contact tracer and monitored COVID-19 positive. Worked with the Public Health Nursing Department for 4 months; April- August 2020. Assisted during the height of the Covid-19 infection to flattening the curve.
- Unit Commendation award: Mass immunizations in 2011.
- Function as Incident Commander, PIO in Chinle Comprehensive Health Care Facility's alternate site exercises.
- Served as Director of Public Health Nursing for 10 years.
- Served as a USPHS Commissioned Officer for 30 years.

Leadership Attributes:

- Supervised twenty-six personnel consisting of professional and support staff.
- Active in community social justice and environmental issues that impact health.
- Partnered with local health programs to increase capacity and effectiveness within the community.

Education, Training, and Professional Development

BSN University of Arizona, Tucson, AZ	June 1986
BS Community Health Education. Univ. of Utah. SLC, UT	August 1978
Public Health Certificate from Johns Hopkins	December 2012
Registered Nurse, State of Arizona	April 2024-Expiration

Career Progression

Title	Agency/location	Pay Grade	Billet Level	Dates
Retired 2016	CSU-Volunteered COVID-19 P	N/A	N/A	4/20-8/20
Director PHN	CSU	0-5	0-6	Jan. 07 -2016
Supervisory, PHN	Tsaile Health Center	0-4	0-4	July 04-Dec. 06
Senior Nurse Specialist	Chinle Service Unit	0-3	0-3	Dec. 02-Jul 04
Nurse Specialist	Chinle Service Unit	0-3	0-3	Jan.00-Dec.02
Nurse Specialist	Chinle Service Unit	0-3	0-3	Jan.98-Jan.00
Senior Nurse	Tsaile Health Center	0-2	0-2	July 90-Jun.98
Clinical Staff Nurse	Chinle Service Unit	0-2	0-2	Oct. 89-Jul.90
Clinical Staff Nurse	Gallup Service Unit	0-2	0-2	Jul 86-Oct.89

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CDR Adella Begaye
Nurse Category, USPHS

Medical Readiness Training.

Special Skills:

- Extensive knowledge in epidemiological process and coordinate outbreak assessment, investigation and containment of diseases such as hantavirus, shigella, salmonella, campylobacter, pertussis. etc.
- Knowledgeable about contact/agencies and network with local, state, and regional agencies in response to outbreaks.
- Fluent in Navajo language and cultural protocols that enhances rapport and trust with community people to advocate on their behalf on public health in the community.
- Active advocate for Navajo people and communities.

Professional Experience

Director of Public Health Nursing:

- Supervised 26 personnel consisting of professional and non-professional staff.
- Responsible for providing services to communities with a user population of 36,000.
- Partnered and collaborated with other local public health programs to increase capacity and effectiveness within the community.
- Ensured the mission of IHS, Public health and Commission Corps are integrated in providing services.

Supervisory Public Health Nurse:

Navajo Reservation, IHS, Tsaile Health Center, Tsaile AZ.

- Supervised PHN department.
- Provided orientation and educated staff to improve quality and efficency of services.
- Established measurable goals and objectives for the department.
- Actively involved in the following committees: Local Emergency Planning Committee, Epidemiological Response Team, Compliance Committee and Sexually Transmitted Disease Task Force.
- Provided leadership in the investigation of communicable disease outbreaks.
- Maintain multi-disciplinary collaboration with health care providers and ancillary dep0artment for patient health care.
- Conducted primary, secondary, and tertiary intervention for individual patient, family and communities.

Nurse Specialist:

- Updated policies and implemented current practices in the decontaminated and sterilization processing for the Central Sterilizing department.

- Updated, implemented and evaluated the Chinle infection control program and employee health program.
- Managed the Infection control program.
- Assured that the IC program et all regulatory and accreditation requirements.
- Provided training to all staff on infection prevention, blood borne exposure and exposures preven5tion.
- Monitored surveillance for communicable diseases and report to approriate services.

Supervisory Clinical Nurse:

Tsaile Health Center

- Managed and directed the ambulatory outpatient department at a satellite station.
- Supervised professional and non-professional staff.
- Planned, set goals and identifiedresources and implemented programs to provide quality care.
- Established staff work performances and evaluated work performances.
- Developed and revised policies and procedures for effective and efficient operation of the clinic.

Staff Nurse:

Chinle AZ.

- Provided nursing care in a 12 bed pediatric unit.
- Implemented nursing process to assess, plan implement and evaluate in providing nursing care to patient.
- Advocated for pediatric patient/parents and encouraged involvement to discharge planning. -

Staff Nurse:

Gallup Indian Medical Center:

- Provided care to pediatric patients in a 24-bed pediatric unit.
- Provided nursing care in special care unit-stabilized critical pediatric patient prior to transport to critical care units.

prepared, litigated, and negotiated imminent endangerment orders for comprehensive investigation and clean up of pollution at Los Alamos National Laboratory, Sandia National Laboratories, and Giant Bloomfield Refinery under the Hazardous Waste Act; handled the bankruptcy litigation in *Mark IV Indus. v. New Mexico* (S.D.N.Y.), successfully arguing that the State's injunctive action for cleanup of groundwater pollution at an industrial site was not discharged in bankruptcy; prepared and litigated more than 25 administrative compliance orders and civil complaints for violations of the N.M. Air Quality Act, N.M. Water Quality Act, N.M. Hazardous Waste Act, and N.M. Radiation Protection Act; negotiated and prepared administrative or judicial settlements in most of these cases.

September 1993
to September
1999

NEW MEXICO OFFICE OF THE ATTORNEY GENERAL
Environmental Enforcement Division
Santa Fe, New Mexico

Assistant Attorney General
Headed a National Association of Attorneys General workgroup on Superfund reauthorization including preparation of extensive comments on proposed amendments in the 103rd, 104th, and 105th Congresses, and presentation of testimony in U.S. Senate and House committee hearings on five occasions; helped start a new State program for bringing natural resource damage claims under CERCLA and the Oil Pollution Act; negotiated several settlements for such claims; represented the State in *New Mexico v. Sparton Technology* (D.N.M.) seeking injunctive relief under RCRA to abate an imminent endangerment from groundwater contamination; represented the State in enforcement actions under the N.M. Water Quality Act; negotiated compliance agreements with the U.S. Department of Energy under the Federal Facility Compliance Act for disposal of stored radioactive waste; prepared and filed *amicus curiae* briefs in several significant federal appellate cases.

August 1991
to September
1993

UNITED STATES DEPARTMENT OF JUSTICE
Environmental Enforcement Section
Washington, D.C.

Special Trial Attorney
Conducted the litigation in *United States v. Butte Water Co.* (D. Mont.) seeking injunctive relief and civil penalties under the Safe Drinking Water Act, including discovery, summary judgment motions, and garnishment of company assets; negotiated a partial settlement for the construction of filtration plants and other injunctive relief totaling $14 million, and a final settlement for a $900,000 civil penalty. The settlement imposed the largest penalty ever obtained under the public water supply provisions of the Safe Drinking Water Act.

September 1985
to September
1993

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
Office of Enforcement
Washington, D.C.

Senior Attorney
Handled all aspects of environmental enforcement litigation under CERCLA, RCRA, the Clean Water Act, and the Safe Drinking Water Act, including pleadings, motions, written discovery, depositions, witness preparation, and trial of several significant cases;

negotiated more than 30 settlements under these statutes, including a CERCLA prospective purchaser agreement and a CERCLA "*de minimis*" settlement involving 177 parties and $11 million; helped prepare the *Exxon Valdez* (D. Alaska) case for litigation; worked with Congressional staff on the 1986 CERCLA reauthorization and drafted proposed amendments; helped develop national enforcement policy under CERCLA, RCRA, and the Safe Drinking Water Act; recognized as a national expert on CERCLA liability, the public water system provisions of the Safe Drinking Water Act, petroleum and used oil issues, and the litigation of imminent endangerment cases.

March to
October 1984

MASSACHUSETTS EXECUTIVE OFFICE OF ENVIRONMENTAL AFFAIRS
Boston, Massachusetts

Assistant General Counsel
Represented the Executive Office on the Special Legislative Commission on Liability for Releases of Hazardous Material and Oil established to report on the adequacy of the legal system in compensating victims of hazardous waste exposure and to recommend legislative reform; worked on the subcommittee that drafted the Commission's Interim Report; helped draft and coordinated the promulgation of amendments to the state "Bottle Deposit Law" regulations and represented the Office in hearings on those amendments.

PUBLICATIONS

United States Court Upholds Regulation of Greenhouse Gas Emissions, 22 European Energy & Environmental Law Review 116 (2013) (Netherlands).

The Disposal of Spent Nuclear Fuel in the United States and Europe: A Persistent Environmental Problem, 34 Harvard Environmental Law Review 461 (2010).

United States Supreme Court Rules on Regulation of Greenhouse Gas Emissions, 17 European Energy & Environmental Law Review 63 (2008) (Netherlands) (with Claybourne F. Clarke).

The Use of Imminent Hazard Provisions of Environmental Laws to Compel Cleanup at Federal Facilities, 27 Stanford Environmental Law Journal 43 (2008).

United States Supreme Court Rules EPA Must Take Action on Greenhouse Gas Emissions: Massachusetts v. EPA, 47 Natural Resources Journal 793 (2007).

Superfund Reauthorization: A More Modest Proposal, 27 Environmental Law Reporter (ELI) 10201 (May 1997).

CERCLA Liability for Pre-Enactment Disposal Activities: Nothing Has Changed, National Environmental Enforcement Journal, Oct. 1996, at 3.

In Praise of Superfund, Environment, Oct. 1993, at 42.

Acid Rain, Canada, and the United States: Enforcing the International Pollution Provision of the Clean Air Act, 1 Boston University International Law Journal 151 (1982).

AWARDS

New Mexico Environment Department and EPA, State-EPA Strategic Partnership Award, Molycorp Mine Remediation, 2003.

U.S. Department of Justice, Environment and Natural Resources Division, Certificate of Commendation, 1997.

EPA Bronze Medal for Commendable Service: *United States v. Butte Water Co.*, 1994.

U.S. Department of Justice, Environment and Natural Resources Division, Certificate of Commendation, 1991.

EPA Bronze Medal for Commendable Service: *United States v. Sanders Lead Co., et al.*, 1991.

EPA Bronze Medal for Commendable Service: *United States v. Hardage, et al.*, 1990.

ADMISSIONS & PROFESSIONAL ACTIVITIES

Admitted: U.S. Supreme Court; U.S. Courts of Appeals for the Fourth, Ninth, Tenth, Eleventh, and D.C. Circuits; U.S. District Court for the District of New Mexico; Supreme Court of New Mexico; Supreme Judicial Court of Massachusetts (inactive).

Member American Bar Association, Section on Environment, Energy, and Resources; New Mexico Bar Association, Section on Natural Resources, Energy, and Environmental Law.

Board President, Conservation Voters New Mexico; Treasurer, Conservation Voters New Mexico Education Fund.

Served on N.M. Governor-Elect Michelle Lujan Grisham's Transition Team for the Environment Department (2018).

EDUCATION

Katholieke Universiteit
Leuven, Belgium
Degree: LL.M. *magna cum laude*, July 2009
Master in Environmental and Energy Law
Internship at ClientEarth, Brussels, Belgium, April-May 2009

Boston University School of Law
Boston, Massachusetts
Degree: J.D., May 1982
Associate Editor, *Boston University International Law Journal*

Boston University College of Liberal Arts
Boston, Massachusetts
Degree: B.A. *cum laude* with Distinction, May 1979
Major: Political Science
Senior Distinction research project identified as one of the year's two best projects: "Law, Politics, and the Supreme Court: *United States v. Nixon.*"

HOBBIES & INTERESTS

Bicycling, skiing, hiking and backpacking, photography, scuba diving, woodworking, world travel.

References and writing sample available on request.

42 USCS § 7503

Current through Public Law 116-193, approved October 30, 2020.

United States Code Service > TITLE 42. THE PUBLIC HEALTH AND WELFARE (Chs. 1 — 161) > CHAPTER 85. AIR POLLUTION PREVENTION AND CONTROL (§§ 7401 — 7671q) > PROGRAMS AND ACTIVITIES (§§ 7401 — 7515) > PLAN REQUIREMENTS FOR NONATTAINMENT AREAS (§§ 7501 — 7515) > Nonattainment Areas in General (§§ 7501 — 7509a)

§ 7503. Permit requirements

(a) In general. The permit program required by section 172(b)(6) shall provide that permits to construct and operate may be issued if—

(1)in accordance with regulations issued by the Administrator for the determination of baseline emissions in a manner consistent with the assumptions underlying the applicable implementation plan approved under section 110 and this part [42 USCS § 7410 and §§ 7501 et seq.], the permitting agency determines that—

(A)by the time the source is to commence operation, sufficient offsetting emissions reductions have been obtained, such that total allowable emissions from existing sources in the region, from new or modified sources which are not major emitting facilities, and from the proposed source will be sufficiently less than total emissions from existing sources (as determined in accordance with the regulations under this paragraph) prior to the application for such permit to construct or modify so as to represent (when considered together with the plan provisions required under section 172 [42 USCS § 7502]) reasonable further progress (as defined in section 171 [42 USCS § 7501]); or

(B)in the case of a new or modified major stationary source which is located in a zone (within the nonattainment area) identified by the Administrator, in consultation with the Secretary of Housing and Urban Development, as a zone to which economic development should be targeted, that emissions of such pollutant resulting from the proposed new or modified major stationary source will not cause or contribute to emissions levels which exceed the allowance permitted for such pollutant for such area from new or modified major stationary sources under section 172(c) [42 USCS § 7502(c)];

(2)the proposed source is required to comply with the lowest achievable emission rate;

(3)the owner or operator of the proposed new or modified source has demonstrated that all major stationary sources owned or operated by such person (or by any entity controlling, controlled by, or under common control with such person) in such State are subject to emission limitations and are in compliance, or on a schedule for compliance, with all applicable emission limitations and standards under this Act; [and]

(4)the Administrator has not determined that the applicable implementation plan is not being adequately implemented for the nonattainment area in which the proposed source is to be constructed or modified in accordance with the requirements of this part [42 USCS §§ 7501 et seq.]; and

(5)an analysis of alternative sites, sizes, production processes, and environmental control techniques for such proposed source demonstrates that benefits of the proposed source significantly outweigh the environmental and social costs imposed as a result of its location, construction, or modification.

Any emission reductions required as a precondition of the issuance of a permit under para
federally enforceable before such permit may be issued.

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Ex. 20

(b) Prohibition on use of old growth allowances. Any growth allowance included in an applicable implementation plan to meet the requirements of section 172(b)(5) [42 USCS § 7502(b)(5)] (as in effect immediately before the date of the enactment of the Clean Air Act Amendments of 1990 [enacted Nov. 15, 1990]) shall not be valid for use in any area that received or receives a notice under section 110(a)(2)(H)(ii) [42 USCS § 7410(a)(2)(H)(ii)] (as in effect immediately before the date of the enactment of the Clean Air Act Amendments of 1990 [enacted Nov. 15, 1990]) or under section 110(k)(1) [42 USCS § 7410(k)(1)] that its applicable implementation plan containing such allowance is substantially inadequate.

(c) Offsets.

(1) The owner or operator of a new or modified major stationary source may comply with any offset requirement in effect under this part [42 USCS §§ 7501 et seq.] for increased emissions of any air pollutant only by obtaining emission reductions of such air pollutant from the same source or other sources in the same nonattainment area, except that the State may allow the owner or operator of a source to obtain such emission reductions in another nonattainment area if (A) the other area has an equal or higher nonattainment classification than the area in which the source is located and (B) emissions from such other area contribute to a violation of the national ambient air quality standard in the nonattainment area in which the source is located. Such emission reductions shall be, by the time a new or modified source commences operation, in effect and enforceable and shall assure that the total tonnage of increased emissions of the air pollutant from the new or modified source shall be offset by an equal or greater reduction, as applicable, in the actual emissions of such air pollutant from the same or other sources in the area.

(2) Emission reductions otherwise required by this Act shall not be creditable as emissions reductions for purposes of any such offset requirement. Incidental emission reductions which are not otherwise required by this Act shall be creditable as emission reductions for such purposes if such emission reductions meet the requirements of paragraph (1).

(d) Control technology information. The State shall provide that control technology information from permits issued under this section will be promptly submitted to the Administrator for purposes of making such information available through the RACT/BACT/LAER clearinghouse to other States and to the general public.

(e) Rocket engines or motors. The permitting authority of a State shall allow a source to offset by alternative or innovative means emission increases from rocket engine and motor firing, and cleaning related to such firing, at an existing or modified major source that tests rocket engines or motors under the following conditions:

(1) Any modification proposed is solely for the purpose of expanding the testing of rocket engines or motors at an existing source that is permitted to test such engines on the date of enactment of this subsection.

(2) The source demonstrates to the satisfaction of the permitting authority of the State that it has used all reasonable means to obtain and utilize offsets, as determined on an annual basis, for the emissions increases beyond allowable levels, that all available offsets are being used, and that sufficient offsets are not available to the source.

(3) The source has obtained a written finding from the Department of Defense, Department of Transportation, National Aeronautics and Space Administration or other appropriate Federal agency, that the testing of rocket motors or engines at the facility is required for a program essential to the national security.

(4) The source will comply with an alternative measure, imposed by the permitting authority, designed to offset any emission increases beyond permitted levels not directly offset by the source. In lieu of imposing any alternative offset measures, the permitting authority may impose an emissions fee to be paid to such authority of a State which shall be an amount no greater than 1.5 times the average cost of stationary source control measures adopted in that area during the previous 3 years. The permitting authority shall utilize the fees in a manner that maximizes the emissions reductions in that area.

History

HISTORY:

Act July 14, 1955, ch. 360, Title I, Part D, Subpart 1, § 173, as added Aug. 7, 1977, P. L. 95-95, Title I, § 129(b), 91 Stat. 748; Nov. 16, 1977, P. L. 95-190, § 14(a)(57), (58), 91 Stat. 1403; Nov. 15, 1990, P. L. 101-549, Title I, § 102(a)(1), (c), 104 Stat. 2412, 2415.

United States Code Service
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End of Document

N.M. Stat. Ann. § 74-6-5

Current with all 2020 legislation, including the 54th Legislature's 2nd Regular and 1st Special sessions

Michie's ™ Annotated Statutes of New Mexico > Chapter 74 Environmental Improvement (Arts. 1 — 13) > Article 6 Water Quality (§§ 74-6-1 — 74-6-17)

74-6-5. Permits; certification; appeals to commission.

A.By regulation, the commission may require persons to obtain from a constituent agency designated by the commission a permit for the discharge of any water contaminant or for the disposal or reuse of septage or sludge.

B.The commission shall adopt regulations establishing procedures for certifying federal water quality permits.

C.Prior to the issuance of a permit, the constituent agency may require the submission of plans, specifications and other relevant information that it deems necessary.

D.The commission shall by regulation set the dates upon which applications for permits shall be filed and designate the time periods within which the constituent agency shall, after the filing of an administratively complete application for a permit, either grant the permit, grant the permit subject to conditions or deny the permit. The constituent agency has the burden of showing that each condition is reasonable and necessary to ensure compliance with the Water Quality Act [74-6-1 NMSA 1978] and applicable regulations, considering site-specific conditions. After regulations have been adopted for a particular industry, permits for facilities in that industry shall be subject to conditions contained in the regulations. Additional conditions on a final permit may be imposed if the applicant is provided with an opportunity to review and provide comments in writing on the draft permit conditions and to receive a written explanation of the reasons for the conditions from the constituent agency.

E.The constituent agency shall deny any application for a permit or deny the certification of a federal water quality permit if:

(1)the effluent would not meet applicable state or federal effluent regulations, standards of performance or limitations;

(2)any provision of the Water Quality Act [74-6-1 NMSA 1978] would be violated;

(3)the discharge would cause or contribute to water contaminant levels in excess of any state or federal standard. Determination of the discharge's effect on ground water shall be measured at any place of withdrawal of water for present or reasonably foreseeable future use. Determination of the discharge's effect on surface waters shall be measured at the point of discharge; or

(4)the applicant has, within the ten years immediately preceding the date of submission of the permit application:

(a)knowingly misrepresented a material fact in an application for a permit;

(b)refused or failed to disclose any information required under the Water Quality Act [74-6-1 NMSA 1978];

(c)been convicted of a felony or other crime involving moral turpitude;

(d)been convicted of a felony in any court for any crime defined by state or federal law as being a restraint of trade, price-fixing, bribery or fraud;

(e)exhibited a history of willful disregard for environmental laws of any state or the

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(f)had an environmental permit revoked or permanently suspended for cause under any environmental laws of any state or the United States.

F.The commission shall by regulation develop procedures that ensure that the public, affected governmental agencies and any other state whose water may be affected shall receive notice of each application for issuance, renewal or modification of a permit. Public notice shall include:

(1)for issuance or modification of a permit:

(a)notice by mail to adjacent and nearby landowners; local, state and federal governments; land grant organizations; ditch associations; and Indian nations, tribes or pueblos;

(b)posting at a place conspicuous to the public and near the discharge or proposed discharge site; and

(c)a display advertisement in English and Spanish in a newspaper of general circulation in the location of the discharge or proposed discharge; provided, however, that the advertisement shall not be displayed in the classified or legal advertisement sections; and

(2)for issuance of renewals of permits:

(a)notice by mail to the interested public, municipalities, counties, land grant organizations, ditch associations and Indian nations, tribes or pueblos; and

(b)a display advertisement in English and Spanish in a newspaper of general circulation in the location of the discharge; provided, however, that the advertisement shall not be displayed in the classified or legal advertisement sections.

G.No ruling shall be made on any application for a permit without opportunity for a public hearing at which all interested persons shall be given a reasonable chance to submit evidence, data, views or arguments orally or in writing and to examine witnesses testifying at the hearing. The hearing shall be recorded. Any person submitting evidence, data, views or arguments shall be subject to examination at the hearing.

H.The commission may adopt regulations for the operation and maintenance of the permitted facility, including requirements, as may be necessary or desirable, that relate to continuity of operation, personnel training and financial responsibility, including financial responsibility for corrective action.

I.Permits shall be issued for fixed terms not to exceed five years, except that for new discharges, the term of the permit shall commence on the date the discharge begins, but in no event shall the term of the permit exceed seven years from the date the permit was issued.

J.By regulation, the commission may impose reasonable conditions upon permits requiring permittees to:

(1)install, use and maintain effluent monitoring devices;

(2)sample effluents and receiving waters for any known or suspected water contaminants in accordance with methods and at locations and intervals as may be prescribed by the commission;

(3)establish and maintain records of the nature and amounts of effluents and the performance of effluent control devices;

(4)provide any other information relating to the discharge or direct or indirect release of water contaminants; and

(5)notify a constituent agency of the introduction of new water contaminants from a new source and of a substantial change in volume or character of water contaminants being introduced from sources in existence at the time of the issuance of the permit.

K.The commission shall provide by regulation a schedule of fees for permits, not exceeding the estimated cost of investigation and issuance, modification and renewal of permits. Fees collected pursuant to this section shall be deposited in the water quality management fund.

L.The issuance of a permit does not relieve any person from the responsibility of complying with the provisions of the Water Quality Act [74-6-1 NMSA 1978], any applicable regulations or water quality standards of the commission or any applicable federal laws, regulations or standards.

M.A permit may be terminated or modified by the constituent agency that issued the permit prior to its date of expiration for any of the following causes:

> **(1)**violation of any condition of the permit;
>
> **(2)**obtaining the permit by misrepresentation or failure to disclose fully all relevant facts;
>
> **(3)**violation of any provisions of the Water Quality Act [74-6-1 NMSA 1978] or any applicable regulations, standard of performance or water quality standards;
>
> **(4)**violation of any applicable state or federal effluent regulations or limitations; or
>
> **(5)**change in any condition that requires either a temporary or permanent reduction or elimination of the permitted discharge.

N.If the constituent agency denies, terminates or modifies a permit or grants a permit subject to condition, the constituent agency shall notify the applicant or permittee by certified mail of the action taken and the reasons. Notice shall also be given by mail to persons who participated in the permitting action.

O.A person who participated in a permitting action before a constituent agency or a person affected by a certification of a federal permit and who is adversely affected by such permitting action or certification may file a petition for review before the commission. Unless a timely petition for review is made, the decision of the constituent agency shall be final and not subject to judicial review. The petition shall:

> **(1)**be made in writing to the commission within thirty days from the date notice is given of the constituent agency's action;
>
> **(2)**include a statement of the issues to be raised and the relief sought; and
>
> **(3)**be provided to all other persons submitting evidence, data, views or arguments in the proceeding before the constituent agency.

P.If a timely petition for review is made, the commission shall consider the petition within ninety days after receipt of the petition. The commission shall notify the petitioner and the applicant or permittee, if other than the petitioner, by certified mail of the date, time and place of the review. If the petitioner is not the applicant or permittee, the applicant or permittee shall be a party to the proceeding. The commission shall ensure that the public receives notice of the date, time and place of the review.

Q.The commission shall review the record compiled before the constituent agency, including the transcript of any public hearing held on the application or draft permit, and shall allow any party to submit arguments. The commission may designate a hearing officer to review the record and the arguments of the parties and recommend a decision to the commission. The commission shall consider and weigh only the evidence contained in the record before the constituent agency and the recommended decision of the hearing officer, if any, and shall not be bound by the factual findings or legal conclusions of the constituent agency. Based on the review of the evidence, the arguments of the parties and recommendations of the hearing officer, the commission shall sustain, modify or reverse the action of the constituent agency. The commission shall enter ultimate findings of fact and conclusions of law and keep a record of the review.

R.Prior to the date set for review, if a party shows to the satisfaction of the commission that there was no reasonable opportunity to submit comment or evidence on an issue being challenged, the commission shall order that additional comment or evidence be taken by the constituent agency. Based on the additional evidence, the constituent agency may revise the decision and shall promptly file with the commission the additional evidence received and action taken. The commission shall consider the additional evidence within ninety days after receipt of the additional evidence and shall notify the petitioner and the applicant or permittee, if other than the petitioner, of the date, time and place of the review.

S.The commission shall notify the petitioner and all other participants in the review proceeding of the action taken by the commission and the reasons for that action.

History

1953 Comp., § 75-39-4.1, enacted by Laws 1973, ch. 326, § 4; 1985, ch. 157, § 1; 1989, ch. 248, § 1; 1993, ch. 100, § 3; 1993, ch. 291, § 5; 1999, ch. 21, § 1; 2005, ch. 195, § 1; 2009, ch. 194, § 2.

Michie's ™ Annotated Statutes of New Mexico
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42 USCS § 6925

Current through Public Law 116-205, approved December 3, 2020.

United States Code Service > TITLE 42. THE PUBLIC HEALTH AND WELFARE (Chs. 1 — 161) > CHAPTER 82. SOLID WASTE DISPOSAL (§§ 6901 — 6992k) > HAZARDOUS WASTE MANAGEMENT (§§ 6921 — 6939g)

§ 6925. Permits for treatment, storage, or disposal of hazardous waste

(a) Permit requirements. Not later than eighteen months after the date of the enactment of this section [enacted Oct. 21, 1976], the administrator shall promulgate regulations requiring each person owning or operating an existing facility or planning to construct a new facility for the treatment, storage, or disposal of hazardous waste identified or listed under this subtitle [42 USCS §§ 6921 et seq.], to have a permit issued pursuant to this section. Such regulations shall take effect on the date provided in section 3010 [42 USCS § 6930] and upon and after such date the treatment, storage, or disposal of any such hazardous waste and the construction of any new facility for the treatment, storage, or disposal of any such hazardous waste is prohibited except in accordance with such a permit. No permit shall be required under this section in order to construct a facility if such facility is constructed pursuant to an approval issued by the Administrator under section 6(e) of the Toxic Substances Control Act [15 USCS § 2605(e)] for the incineration of polychlorinated biphenyls and any person owning or operating such a facility may, at any time after operation or construction of such facility has begun, file an application for a permit pursuant to this section authorizing such facility to incinerate hazardous waste identified or listed under this subtitle [42 USCS §§ 6921 et seq.].

(b) Requirements of permit application. Each application for a permit under this section shall contain such information as may be required under regulations promulgated by the Administrator, including information respecting—

> **(1)**estimates with respect to the composition, quantities, and concentrations of any hazardous waste identified or listed under this subtitle [42 USCS §§ 6921 et seq.], or combinations of any such hazardous waste and any other solid waste, proposed to be disposed of, treated, transported, or stored, and the time, frequency, or rate of which such waste is proposed to be disposed of, treated, transported, or stored; and
>
> **(2)**the site at which such hazardous waste or the products of treatment of such hazardous waste will be disposed of, treated, transported to, or stored.

(c) Permit issuance.

> **(1)**Upon a determination by the Administrator (or a State, if applicable), of compliance by a facility for which a permit is applied for under this section with the requirements of this section and section 3004 [42 USCS § 6924], the Administrator (or the State) shall issue a permit for such facilities. In the event permit applicants propose modification of their facilities, or in the event the Administrator (or the State) determines that modifications are necessary to conform to the requirements under this section and section 3004 [42 USCS § 6924], the permit shall specify the time allowed to complete the modifications.
>
> **(2)**
>
> > **(A)**
> >
> > > **(i)**Not later than the date four years after the enactment of the Hazardous and Solid Waste Amendments of 1984 [enacted Nov. 8, 1984], in the case of each application u
> > > subsection for a permit for a land disposal facility which was submitted before

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Administrator shall issue a final permit pursuant to such application or issue a final denial of such application.

(ii) Not later than the date five years after the enactment of the Hazardous and Solid Waste Amendments of 1984 [enacted Nov. 8, 1984], in the case of each application for a permit under this subsection for an incinerator facility which was submitted before such date, the Administrator shall issue a final permit pursuant to such application or issue a final denial of such application.

(B) Not later than the date eight years after the enactment of the Hazardous and Solid Waste Amendments of 1984 [enacted Nov. 8, 1984], in the case of each application for a permit under this subsection for any facility (other than a facility referred to in subparagraph (A)) which was submitted before such date, the Administrator shall issue a final permit pursuant to such application or issue a final denial of such application.

(C) The time periods specified in this paragraph shall also apply in the case of any State which is administering an authorized hazardous waste program under section 3006 [42 USCS § 6926]. Interim status under subsection (e) shall terminate for each facility referred to in subparagraph (A)(ii) or (B) on the expiration of the five- or eight-year period referred to in subparagraph (A) or (B), whichever is applicable, unless the owner or operator of the facility applies for a final determination regarding the issuance of a permit under this subsection within—

(i)two years after the date of the enactment of the Hazardous and Solid Waste Amendments of 1984 [enacted Nov. 8, 1984] (in the case of a facility referred to in subparagraph (A)(ii)), or

(ii)four years after such date of enactment (in the case of a facility referred to in subparagraph (B)).

(3) Any permit under this section shall be for a fixed term, not to exceed 10 years in the case of any land disposal facility, storage facility, or incinerator or other treatment facility. Each permit for a land disposal facility shall be reviewed five years after date of issuance or reissuance and shall be modified as necessary to assure that the facility continues to comply with the currently applicable requirements of this section and section 3004 [42 USCS § 6924]. Nothing in this subsection shall preclude the Administrator from reviewing and modifying a permit at any time during its term. Review of any application for a permit renewal shall consider improvements in the state of control and measurement technology as well as changes in applicable regulations. Each permit issued under this section shall contain such terms and conditions as the Administrator (or the State) determines necessary to protect human health and the environment.

(d) Permit revocation. Upon a determination by the Administrator (or by a State, in the case of a State having an authorized hazardous waste program under section 3006 [42 USCS § 6926]) of noncompliance by a facility having a permit under this title [42 USCS §§ 6901 et seq.] with the requirements of this section or section 3004 [42 USCS § 6924], the Administrator (or State, in the case of a State having an authorized hazardous waste program under section 3006 [42 USCS § 6926]) shall revoke such permit.

(e) Interim status.

(1) Any person who—

(A)owns or operates a facility required to have a permit under this section which facility—

(i)was in existence on November 19, 1980, or

(ii)is in existence on the effective date of statutory or regulatory changes under this Act [42 USCS §§ 6901 et seq.] that render the facility subject to the requirement to have a permit under this section,

(B)has complied with the requirements of section 3010(a) [42 USCS § 6930(a)], and

(C)has made an application for a permit under this section, shall be treated as having been issued such permit until such time as final administrative disposition of such application is made, unless the Administrator or other plaintiff proves that final administrative disposition of such application has not been made because of the failure of the applicant to furnish information reasonably required or requested in order to process the application.

This paragraph shall not apply to any facility which has been previously denied a permit under this section or if authority to operate the facility under this section has been previously terminated.

(2) In the case of each land disposal facility which has been granted interim status under this subsection before the date of enactment of the Hazardous and Solid Waste Amendments of 1984 [enacted Nov. 8, 1984], interim status shall terminate on the date twelve months after the date of the enactment of such Amendments [enacted Nov. 8, 1984] unless the owner or operator of such facility—

(A)applies for a final determination regarding the issuance of a permit under subsection (c) for such facility before the date twelve months after the date of the enactment of such Amendments [enacted Nov. 8, 1984]; and

(B)certifies that such facility is in compliance with all applicable groundwater monitoring and financial responsibility requirements.

(3) In the case of each land disposal facility which is in existence on the effective date of statutory or regulatory changes under this Act [42 USCS §§ 6901 et seq.] that render the facility subject to the requirement to have a permit under this section and which is granted interim status under this subsection, interim status shall terminate on the date twelve months after the date on which the facility first becomes subject to such permit requirement unless the owner or operator of such facility—

(A)applies for a final determination regarding the issuance of a permit under subsection (c) for such facility before the date twelve months after the date on which the facility first becomes subject to such permit requirement; and

(B)certifies that such facility is in compliance with all applicable groundwater monitoring and financial responsibility requirements.

(f) Coal mining wastes and reclamation permits. Notwithstanding subsection (a) through (e) of this section, any surface coal mining and reclamation permit covering any coal mining wastes or overburden which has been issued or approved under the Surface Mining Control and Reclamation Act of 1977 shall be deemed to be a permit issued pursuant to this section with respect to the treatment, storage, or disposal of such wastes or overburden. Regulations promulgated by the Administrator under this subtitle [42 USCS §§ 6921 et seq.] shall not be applicable to treatment, storage, or disposal of coal mining wastes and overburden which are covered by such a permit.

(g) Research, development, and demonstration permits.

(1) The Administrator may issue a research, development, and demonstration permit for any hazardous waste treatment facility which proposes to utilize an innovative and experimental hazardous waste treatment technology or process for which permit standards for such experimental activity have not been promulgated under this subtitle [42 USCS §§ 6921 et seq.]. Any such permit shall include such terms and conditions as will assure protection of human health and the environment. Such permits—

(A)shall provide for the construction of such facilities, as necessary, and for operation of the facility for not longer than one year (unless renewed as provided in paragraph (4)), and

(B)shall provide for the receipt and treatment by the facility of only those types and quantities of hazardous waste which the Administrator deems necessary for purposes of determining the efficacy and performance capabilities of the technology or process and the effects of such technology or process on human health and the environment, and

(C)shall include such requirements as the Administrator deems necessary to protect human health and the environment (including, but not limited to, requirements regarding monitoring, operation, insurance or bonding, financial reponsibility [responsibility], closure, and remedial action), and such requirements as the Administrator deems necessary regarding testing and providing of information to the Administrator with respect to the operation of the facility.

The Administrator may apply the criteria set forth in this paragraph in establishing the conditions of each permit without separate establishment of regulations implementing such criteria.

(2) For the purpose of expediting review and issuance of permits under this subsection, the Administrator may, consistent with the protection of human health and the environment, modify or waive permit application and permit issuance requirements established in the Administrator's general permit regulations except that there may be no modification or waiver of regulations regarding financial responsibility (including insurance) or of procedures established under section 7004(b)(2) [42 USCS § 6974(b)(2)] regarding public participation.

(3) The Administrator may order an immediate termination of all operations at the facility at any time he determines that termination is necessary to protect human health and the environment.

(4) Any permit issued under this subsection may be renewed not more than three times. Each such renewal shall be for a period of not more than 1 year.

(h) Waste minimization. Effective September 1, 1985, it shall be a condition of any permit issued under this section for the treatment, storage, or disposal of hazardous waste on the premises where such waste was generated that the permittee certify, no less often than annually, that—

(1)the generator of the hazardous waste has a program in place to reduce the volume or quantity and toxicity of such waste to the degree determined by the generator to be economically practicable; and

(2)the proposed method of treatment, storage, or disposal is that practicable method currently available to the generator which minimizes the present and future threat to human health and the environment.

(i) Interim status facilities receiving wastes after July 26, 1982. The standards concerning ground water monitoring, unsaturated zone monitoring, and corrective action, which are applicable under section 3004 [42 USCS § 6924] to new landfills, surface impoundments, land treatment units, and waste-pile units required to be permitted under subsection (c) shall also apply to any landfill, surface impoundment, land treatment unit, or waste-pile unit qualifying for the authorization to operate under subsection (e) which receives hazardous waste after July 26, 1982.

(j) Interim status surface impoundments.

(1) Except as provided in paragraph (2), (3), or (4), each surface impoundment in existence on the date of enactment of the Hazardous and Solid Waste Amendments of 1984 [Nov. 8, 1984] and qualifying for the authorization to operate under subsection (e) of this section shall not receive, store, or treat hazardous waste after the date four years after such date of enactment unless such surface impoundment is in compliance with the requirements of section 3004(o)(1)(A) [42 USCS § 6924(o)(1)(A)] which would apply to such impoundment if it were new.

(2) Paragraph (1) of this subsection shall not apply to any surface impoundment which (A) has at least one liner, for which there is no evidence that such liner is leaking; (B) is located more than one-quarter mile from an underground source of drinking water; and (C) is in compliance with generally applicable ground water monitoring requirements for facilities with permits under subsection (c) of this section.

(3) Paragraph (1) of this subsection shall not apply to any surface impoundment which (A) contains treated waste water during the secondary or subsequent phases of an aggressive biological treatment facility subject to a permit issued under section 402 of the Clean Water Act [33 USCS § 1342] (or which holds such treated waste water after treatment and prior to discharge); (B) is in compliance with generally applicable ground water monitoring requirements for facilities with permits under subsection (c) of this section; and (C)(i) is part of a facility in compliance with section 301(b)(2) of the Clean Water Act [33 USCS § 1311(b)(2)] or (ii) in the case of a facility for which no effluent guidelines required under section 304(b)(2) of the Clean Water Act [33 USCS § 1314(b)(2)] are in effect and no permit under section 402(a)(1) of such Act [33 USCS § 1342(a)(1)] implementing section 301(b)(2) of such Act [33

USCS § 1311(b)(2)] has been issued, is part of a facility in compliance with a permit under section 402 of such Act [33 USCS § 1342], which is achieving significant degradation of toxic pollutants and hazardous constituents contained in the untreated waste stream and which has identified those toxic pollutants and hazardous constituents in the untreated waste stream to the appropriate permitting authority.

(4) The Administrator (or the State, in the case of a State with an authorized program), after notice and opportunity for comment, may modify the requirements of paragraph (1) for any surface impoundment if the owner or operator demonstrates that such surface impoundment is located, designed and operated so as to assure that there will be no migration of any hazardous constitutent [constituent] into ground water or surface water at any future time. The Administrator or the State shall take into account locational criteria established under section 3004(o)(7) [42 USCS § 6924(o)(7)].

(5) The owner or operator of any surface impoundment potentially subject to paragraph (1) who has reason to believe that on the basis of paragraph (2), (3), or (4) such surface impoundment is not required to comply with the requirements of paragraph (1), shall apply to the Administrator (or the State, in the case of a State with an authorized program) not later than twenty-four months after the date of enactment of the Hazardous and Solid Waste Amendments of 1984 [enacted Nov. 8, 1984] for a determination of the applicability of paragraph (1) (in the case of paragraph (2) or (3)) or for a modification of the requirements of paragraph (1) (in the case of paragraph (4)), with respect to such surface impoundment. Such owner or operator shall provide, with such application, evidence pertinent to such decision, including:

(A)an application for a final determination regarding the issuance of a permit under subsection (c) of this section for such facility, if not previously submitted;

(B)evidence as to compliance with all applicable ground water monitoring requirements and the information and analysis from such monitoring;

(C)all reasonably ascertainable evidence as to whether such surface impoundment is leaking; and

(D)in the case of applications under paragraph (2) or (3), a certification by a registered professional engineer with academic training and experience in ground water hydrology that—

(i)under paragraph (2), the liner of such surface impoundment is designed, constructed, and operated in accordance with applicable requirements, such surface impoundment is more than one-quarter mile from an underground source of drinking water and there is no evidence such liner is leaking; or

(ii)under paragraph (3), based on analysis of those toxic pollutants and hazardous constituents that are likely to be present in the untreated waste stream, such impoundment satisfies the conditions of paragraph (3).

In the case of any surface impoundment for which the owner or operator fails to apply under this paragraph within the time provided by this paragraph or paragraph (6), such surface impoundment shall comply with paragraph (1) notwithstanding paragraph (2), (3), or (4). Within twelve months after receipt of such application and evidence and not later than thirty-six months after such date of enactment [enacted Nov. 8, 1984], and after notice and opportunity to comment, the Administrator (or, if appropriate, the State) shall advise such owner or operator on the applicability of paragraph (1) to such surface impoundment or as to whether and how the requirements of paragraph (1) shall be modified and applied to such surface impoundment.

(6)

(A) In any case in which a surface impoundment becomes subject to paragraph (1) after the date of enactment of the Hazardous and Solid Waste Amendments of 1984 [enacted Nov. 8, 1984] due to the promulgation of additional listings or characteristics for the identification of hazardous waste under section 3001 [42 USCS § 6921], the period for compliance in paragraph (1) shall be four years after the date of such promulgation, the period for demonstrations under paragraph (4) and for submission of evidence under paragraph (5) shall be not later than twenty-four months after the date of such promulgation, and the period for the Administrator (or if appropriate, the State) to advise such owners or operators under paragraph (5) shall be not later than thirty-six months after the date of promulgation.

(B) In any case in which a surface impoundment is initially determined to be excluded from the requirements of paragraph (1) but due to a change in condition (including the existence of a leak) no longer satisfies the provisions of paragraph (2), (3), or (4) and therefore becomes subject to paragraph (1), the period for compliance in paragraph (1) shall be two years after the date of discovery of such change of condition, or in the case of a surface impoundment excluded under paragraph (3) three years after such date of discovery.

(7)

(A) The Administrator shall study and report to the Congress on the number, range of size, construction, likelihood of hazardous constituents migrating into ground water, and potential threat to human health and the environment of existing surface impoundments excluded by paragraph (3) from the requirements of paragraph (1). Such report shall address the need, feasibility, and estimated costs of subjecting such existing surface impoundments to the requirements of paragraph (1).

(B) In the case of any existing surface impoundment or class of surface impoundments from which the Administrator (or the State, in the case of a State with an authorized program) determines hazardous constituents are likely to migrate into ground water, the Administrator (or if appropriate, the State) is authorized to impose such requirements as may be necessary to protect human health and the environment, including the requirements of section 3004(o) [42 USCS § 6924(o)] which would apply to such impoundments if they were new.

(C) In the case of any surface impoundment excluded by paragraph (3) from the requirements of paragraph (1) which is subsequently determined to be leaking, the Administrator (or, if appropriate, the State) shall require compliance with paragraph (1), unless the Administrator (or, if appropriate, the State) determines that such compliance is not necessary to protect human health and the environment.

(8) In the case of any surface impoundment in which the liners and leak detection system have been installed pursuant to the requirements of paragraph (1) and in good faith compliance with section 3004(o) [42 USCS § 6924(o)] and the Administrator's regulations and guidance documents governing liners and leak detection systems, no liner or leak detection system which is different from that which was so installed pursuant to paragraph (1) shall be required for such unit by the Administrator when issuing the first permit under this section to such facility. Nothing in this paragraph shall preclude the Administrator from requiring installation of a new liner when the Administrator has reason to believe that any liner installed pursuant to the requirements of this subsection is leaking.

(9) In the case of any surface impoundment which has been excluded by paragraph (2) on the basis of a liner meeting the definition under paragraph (12)(A)(ii), at the closure of such impoundment the Administrator shall require the owner or operator of such impoundment to remove or decontaminate all waste residues, all contaminated liner material, and contaminated soil to the extent practicable. If all contaminated soil is not removed or decontaminated, the owner or operator of such impoundment shall be required to comply with appropriate post-closure requirements, including but not limited to ground water monitoring and corrective action.

(10) Any incremental cost attributable to the requirements of this subsection or section 3004(o) [42 USCS § 6924(o)] shall not be considered by the Administrator (or the State, in the case of a State with an authorized program under section 402 of the Clean Water Act [33 USCS § 1342])—

(A)in establishing effluent limitations and standards under section 301, 304, 306, 307, or 402 of the Clean Water Act [33 USCS § 1311, 1314, 1316, or 1317] based on effluent limitations guidelines and standards promulgated any time before twelve months after the date of enactment of the Hazardous and Solid Waste Amendments of 1984 [enacted Nov. 8, 1984]; or

(B)in establishing any other effluent limitations to carry out the provisions of section 301, 307, or 402 of the Clean Water Act [33 USCS § 1311, 1317, or 1342] on or before October 1, 1986.

(11)

(A) If the Administrator allows a hazardous waste which is prohibited from one or more methods of land disposal under subsection (d), (e), or (g) of section 3004 [42 USCS § 6924(d), (e) or (g)] (or under regulations promulgated by the Administrator under such subsections) to be placed in a surface impoundment (which is operating pursuant to interim status) for storage or treatment, such impoundment shall meet the requirements that are applicable to new surface impoundments under section 3004(o)(1) [42 USCS § 6924(o)(1)], unless such impoundment meets the requirements of paragraph (2) or (4).

(B) In the case of any hazardous waste which is prohibited from one or more methods of land disposal under subsection (d), (e), or (g) of section 3004 [42 USCS § 6924(d), (e), or (g)] (or under regulations promulgated by the Administrator under such subsection) the placement or maintenance of such hazardous waste in a surface impoundment for treatment is prohibited as of the effective date of such prohibition unless the treatment residues which are hazardous are, at a minimum, removed for subsequent management within one year of the entry of the waste into the surface impoundment.

(12)

(A) For the purposes of paragraph (2)(A) of this subsection, the term "liner" means—

(i)a liner designed, constructed, installed, and operated to prevent hazardous waste from passing into the liner at any time during the active life of the facility; or

(ii)a liner designed, constructed, installed, and operated to prevent hazardous waste from migrating beyond the liner to adjacent subsurface soil, ground water, or surface water at any time during the active life of the facility.

(B) For the purposes of this subsection, the term "aggressive biological treatment facility" means a system of surface impoundments in which the initial impoundment of the secondary treatment segment of the facility utilizes intense mechanical aeration to enhance biological activity to degrade waste water pollutants and

(i)the hydraulic retention time in such initial impoundment is no longer than 5 days under normal operating conditions, on an annual average basis;

(ii)the hydraulic retention time in such initial impoundment is no longer than thirty days under normal operating conditions, on an annual average basis: *Provided,* That the sludge in such impoundment does not constitute a hazardous waste as identified by the extraction procedure toxicity characteristic in effect on the date of enactment of the Hazardous and Solid Waste Amendments of 1984 [enacted Nov. 8, 1984]; or

(iii)such system utilizes activated sludge treatment in the first portion of secondary treatment.

(C) For the purposes of this subsection, the term "underground source or [of] drinking water" has the same meaning as provided in regulations under the Safe Drinking Water Act (title XIV of the Public Health Service Act).

(13) The Administrator may modify the requirements of paragraph (1) in the case of a surface impoundment for which the owner or operator, prior to October 1, 1984, has entered into, and is in compliance with, a consent order, decree, or agreement with the Administrator or a State with an authorized program mandating corrective action with respect to such surface impoundment that provides a degree of protection of human health and the environment which is at a minimum equivalent to that provided by paragraph (1).

History

HISTORY:

Act Oct. 20, 1965, P. L. 89-272, Title II, Subtitle C, § 3005, as added Oct. 21, 1976, P. L. 94-580, § 2, 90 Stat. 2808; Nov. 8, 1978, P. L. 95-609, § 7(h), 92 Stat. 3082; Oct. 21, 1980, P. L. 96-482, §§ 10, 11, 94 Stat. 2338; Nov. 8, 1984, P. L. 98-616, Title II, Subtitle B, §§ 211–213(a), (c), 214, 215, Subtitle C, § 222(b), Subtitle D, § 243(c), 98 Stat. 3240-3243, 3253, 3261; March 26, 1996, P. L. 104-119, § 4(6), (7), 110 Stat. 833.

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PROFILE

International environmental and human rights attorney with expertise in Colorado air law, oil and gas regulations, climate change policy, environmental governance, gender equality, and international network leadership. 20 years of experience working with communities and building advocacy coalitions with UN agencies, governments, private sector and diverse civil society organizations on international and domestic climate change law and policy, environmental governance, and indigenous land rights.

EDUCATION

The George Washington University Law School, Washington, D.C.
J.D., May 2004
- Member, George Washington University Law School Moot Court Board
- President, Environmental Law Association
- Grant Recipient, Equal Justice Foundation

Université Robert Schuman, Strasbourg, France
D.E.S.S., Environmental Law and Land Management, January 1998
D.U.P.N., Diploma of Pollution and Nuisances, May 1997

University of Colorado, Boulder, Colorado
B.A. Cum Laude, International Affairs, May 1995

Institut d'Etudes Politiques (I.E.P.), Grenoble, France
Certificate of Political Studies (C.E.P.), May 1994

PROFESSIONAL EXPERIENCE

Earthworks, Washington, D.C. November 2017 – present
Field Advocate – CO & NM

Lead fieldwork in oil and gas fields and document otherwise invisible oil and gas pollution using an Optical Gas Imaging camera. Collaborate with and support impacted communities in CO and NM. Conduct research to inform and influence regulatory and legislative decision-making.

Lake County Build a Generation, Leadville, CO
Healthy Kids Director, Get Outdoors Leadville! (GOL!) January 2017 – December 2017
Co-Coordinator, Get Outdoors Leadville! (GOL!) June – December 2017

Facilitated over 100 community consultations for $4.6 million proposal to GOCO to support connecting Lake County youth to nature. Coordinated community input for final proposal.

World Resources Institute (WRI), Washington, D.C. May 2014 – June 2016
Operations Manager, Climate Briefing Service (CBS)

Built operational infrastructure for new international climate initiative focused on climate diplomacy and unbranded communications. Facilitated collaboration with key sectors and decision-makers. Managed international team and annual budget of over $5 million.

Global Gender and Climate Alliance (GGCA) April 2011 – March 2014
Coordinator, GGCA Secretariat

Directed international network of over 90 UN agencies and civil society organizations. Drafted unprecedented UNFCCC provisions for gender equality and human rights.

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Colorado Attorney General's Office, Denver, CO October 2007 – February 2011
Assistant Attorney General, Division of Natural Resources and Environment
Represented State agencies in administrative and enforcement air matters.
Conducted legal research regarding the Clean Air Act and State regulations.

Colorado State District Court, Denver, CO November 2006 – October 2007
Law Clerk, Judge Christina M. Habas
Conducted legal research for civil and criminal cases. Prepared legal memos and draft orders. Served as bailiff for civil and criminal trials. Managed courtroom pleadings.

World Resources Institute, Washington, D.C. March 2003 – February 2006
Senior Associate, Institutions and Governance Program
Conducted environmental governance trainings in Asia and Africa. Led global NGO network of environmental governance advocates, focusing on access to justice indicators.

Amerindian Peoples Association, Georgetown, Guyana June – August 2002
Law Clerk, Amerindian Legal Services Centre
Co-facilitated legal trainings in the Guyanese Interior. Drafted formal Amerindian land claim application. Conducted comparative international legal analysis of indigenous rights.

U.S. Climate Action Network, Washington, D.C. September 1998 – May 2001
International Coordinator
Chaired policy consensus among 300+ international NGO members.
Advocated for first indigenous participation in climate policy negotiations.

Center for International Environmental Law, Washington, D.C. September 1998 – September 1999
Program Associate, Climate Change Program
Prepared advocacy research and presentations for international climate workshops.

United Nations Climate Change Secretariat (UNFCCC), Bonn, Germany May 1997 – July 1998
Program Officer, Cooperative Implementation Team
Assisted in drafting UN documents for international climate negotiations. Managed workshop facilitation for technical UNFCCC meetings focused on the CDM and JI.

SELECT PUBLICATIONS AND RESEARCH

- ***"Putting the Public First: How CDPHE can overcome its legacy of prioritizing oil and gas industry interests ahead of public health, safety, welfare and the environment,"*** Earthworks, March 2020.
- ***"New Mexico's Shale Snapshot – Permian Basin,"*** Earthworks, November 2019.
- ***"New Mexico's Moving Ahead – Restoring the Oil Conservation Division's Strength and Authority,"*** Earthworks, January 2019.
- ***"Exposing Gender Gaps in Financing Climate Change Mitigation – and Proposing Solutions,"*** Co-author, GGCA, WEDO & ENERGIA, November 2013.
- ***"The Access Initiative Assessment Toolkit: Evaluating the Foundations of Environmental Governance,"*** Contributing author, World Resources Institute, April 2006.
- ***"Public Participation in the Clean Development Mechanism and Joint Implementation,"*** Making Kyoto Work: Legal Aspects of Implementing the Kyoto Protocol Mechanisms, World Bank, April 2005.
- ***"Public Participation in the Clean Development Mechanism of the Kyoto Protocol,"*** Glenn Wiser, Co-author, The New Public: The Globalization of Public Participation, Environmental Law Institute, 2002.

LANGUAGES

- Fluent French
- Basic Spanish

EARTHWORKS

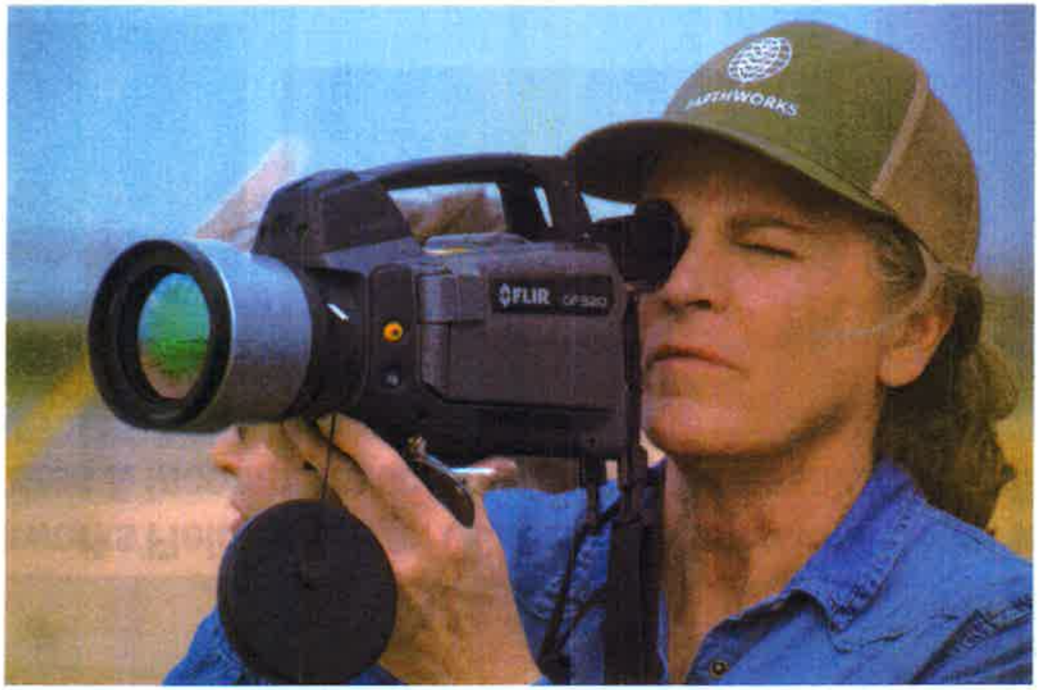
Protecting communities & the environment from the adverse impacts of
mineral & energy development while promoting sustainable solutions.

Earthworks Field Findings: Oil and Gas Emissions from Flares: unlit flares & incomplete combustion by flares (aka "dirty flares")

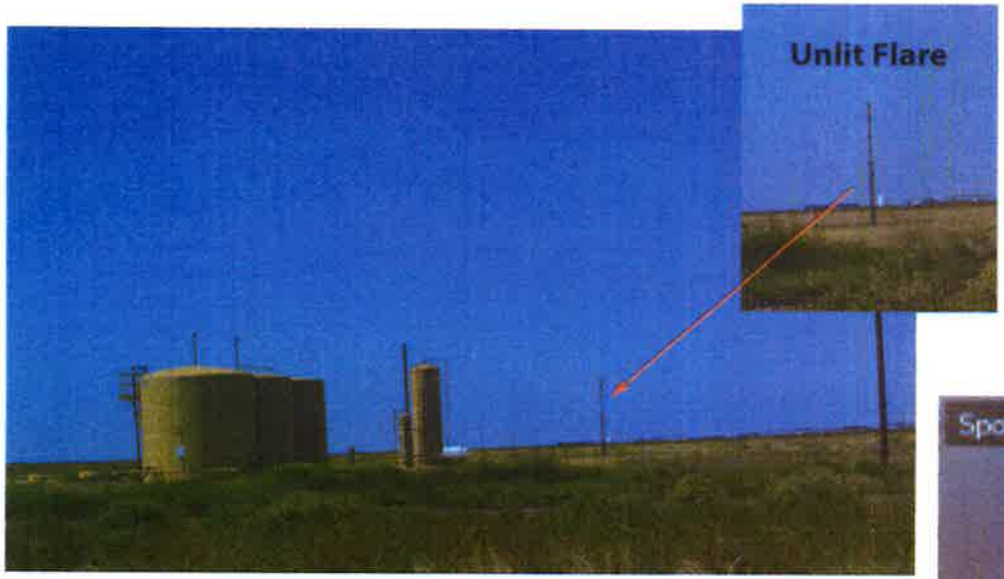
CA
Ex. 24

Optical Gas Imaging (OGI): making invisible gas VISIBLE

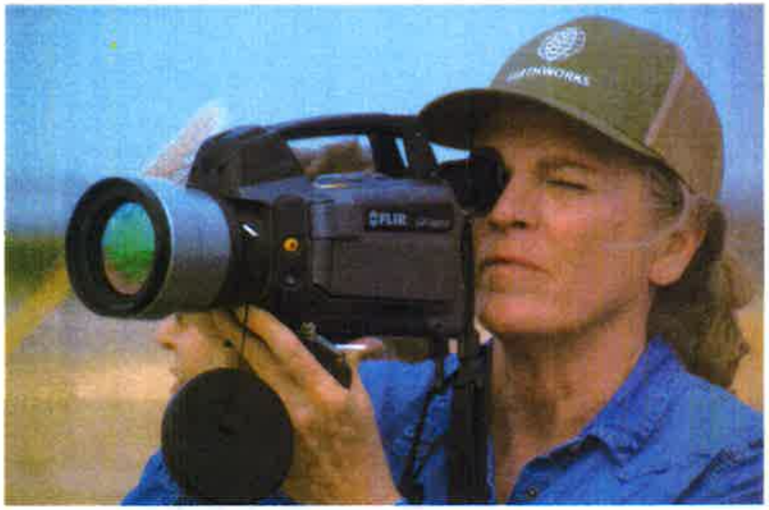
- **Identify** problems (odors, health symptom) and likely sources
- **Partner** with impacted community members
- **Expose** normally invisible pollution using OGI
- **File complaints** based on local, state, and federal

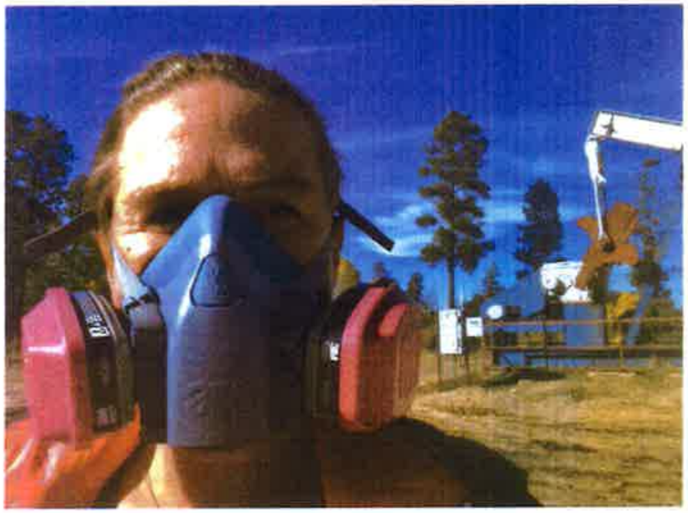


Seeing is believing!

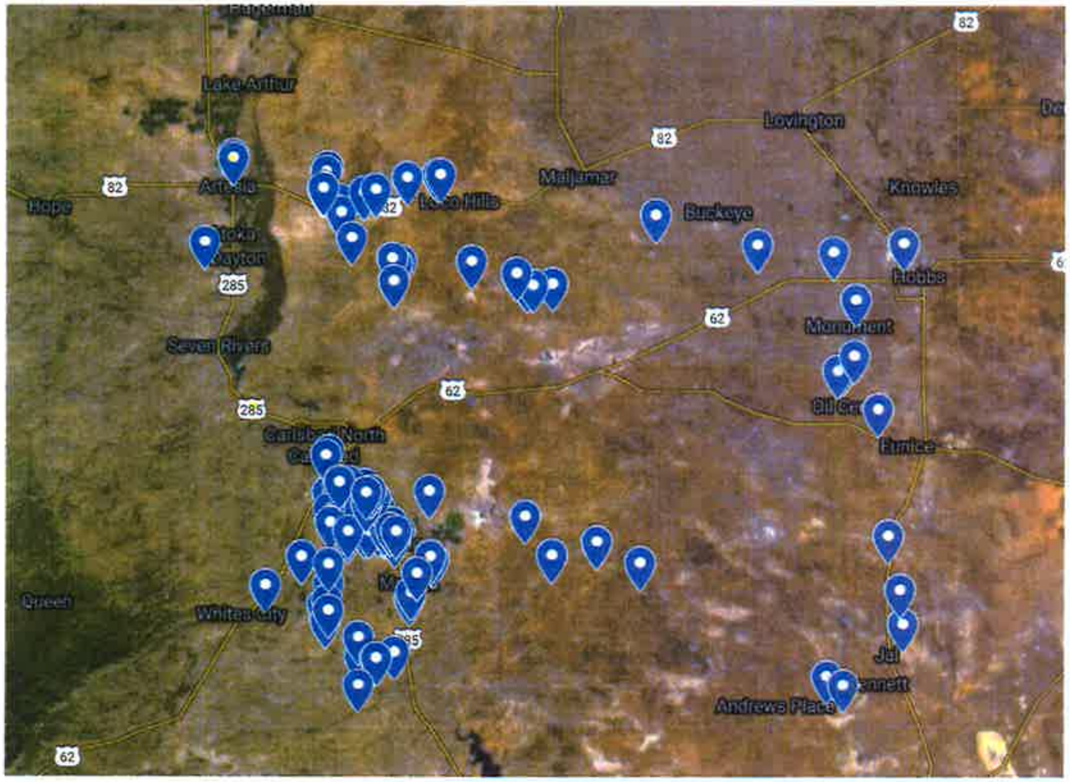


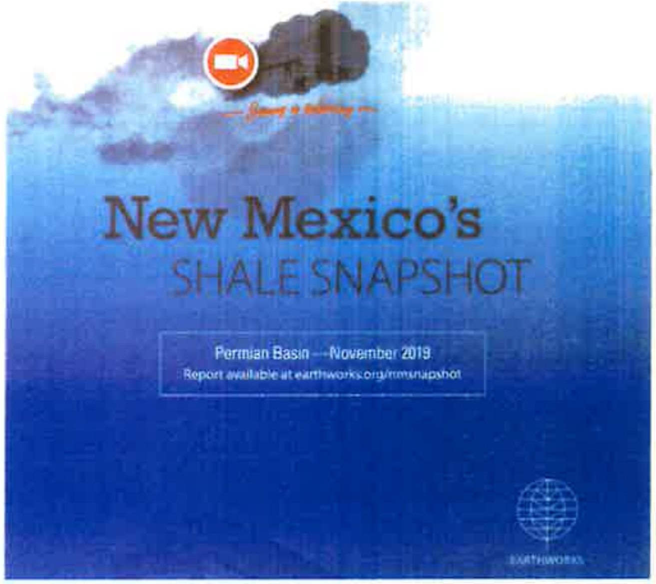
Earthworks fieldwork tool box





Permian region

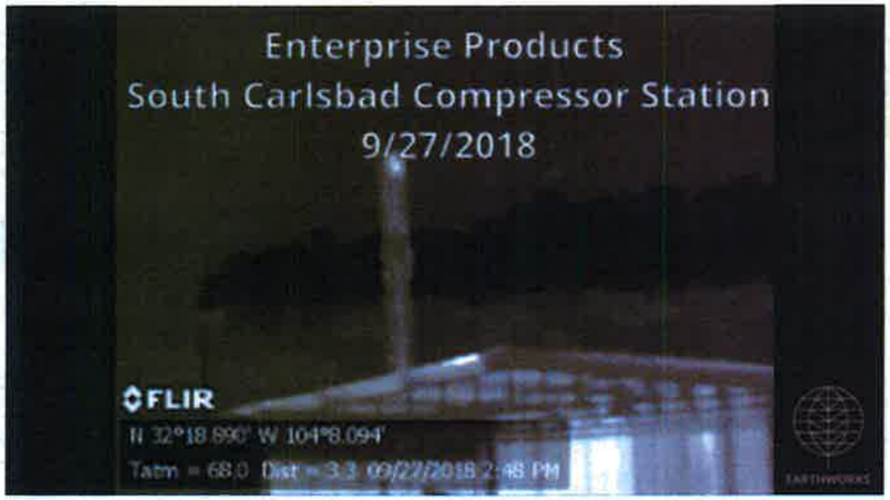



New Mexico's
SHALE SNAPSHOT

Permian Basin — November 2019
Report available at earthworks.org/nmsnapshot

EARTHWORKS

Enterprise: South Carlsbad Compressor Station
Loving, NM (just south of Carlsbad)

September 2018 *Blowdown / unlit flare*	**November 2019** *Dirty / unlit flare*
	

Matador: Kathy Coleman site – Carlsbad
Unlit flare lasting 5+ days - January 2019

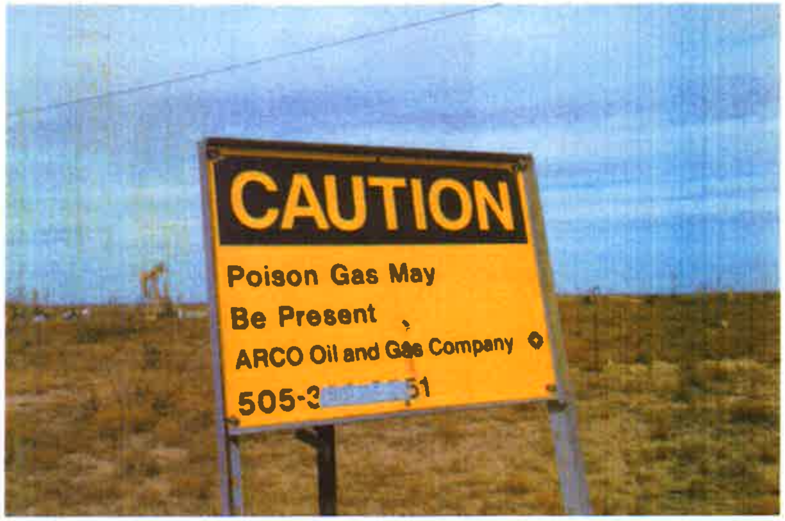
Matador: Kathy Coleman site (Carlsbad)
Unlit flare – March 2018

November 9 site visit

Caza Operating: Alisa Ogden 15 Well site

Unlit flare

Loco Hills legacy fields (between Artesia and Lovington)

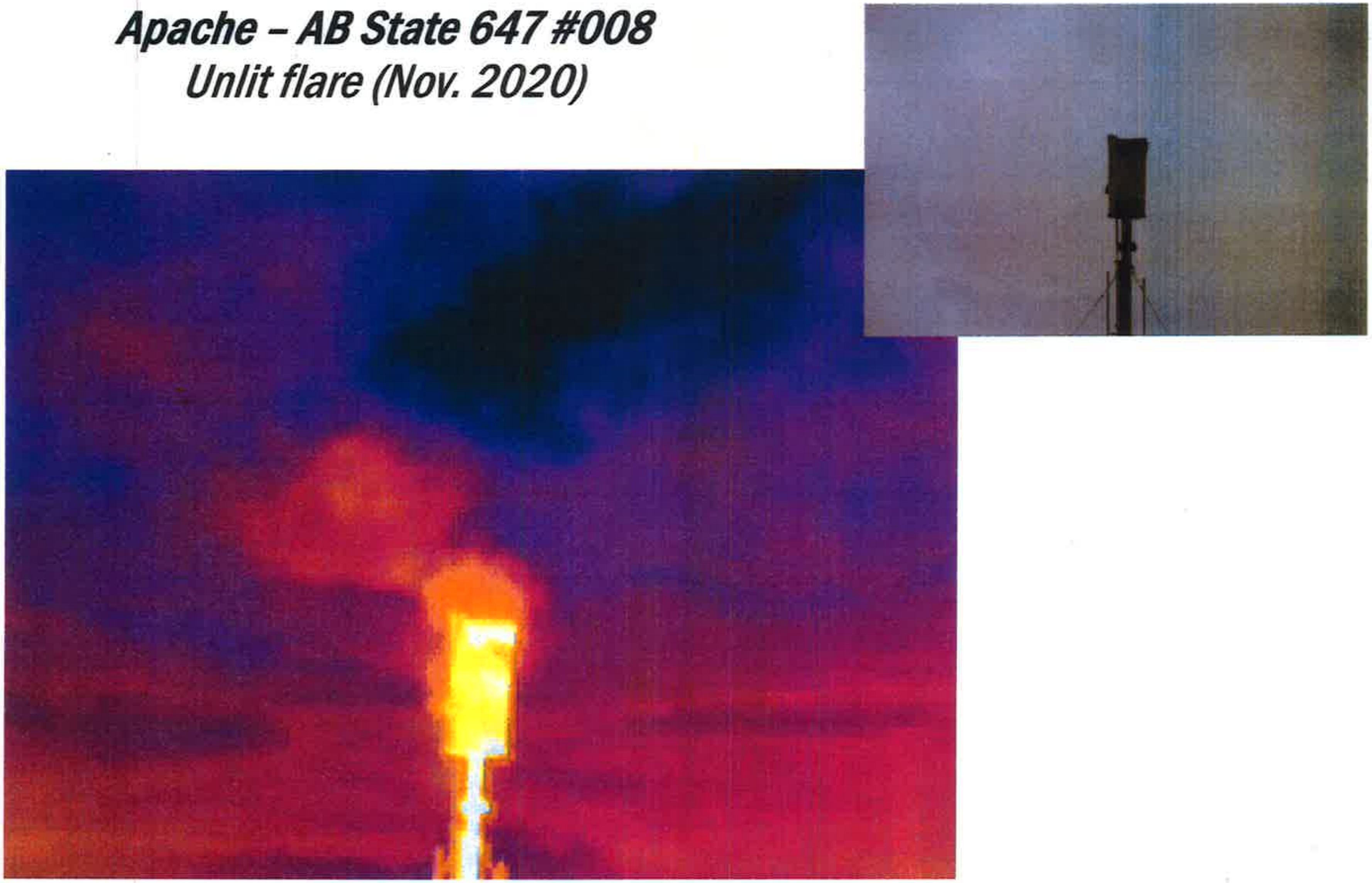


WARNING

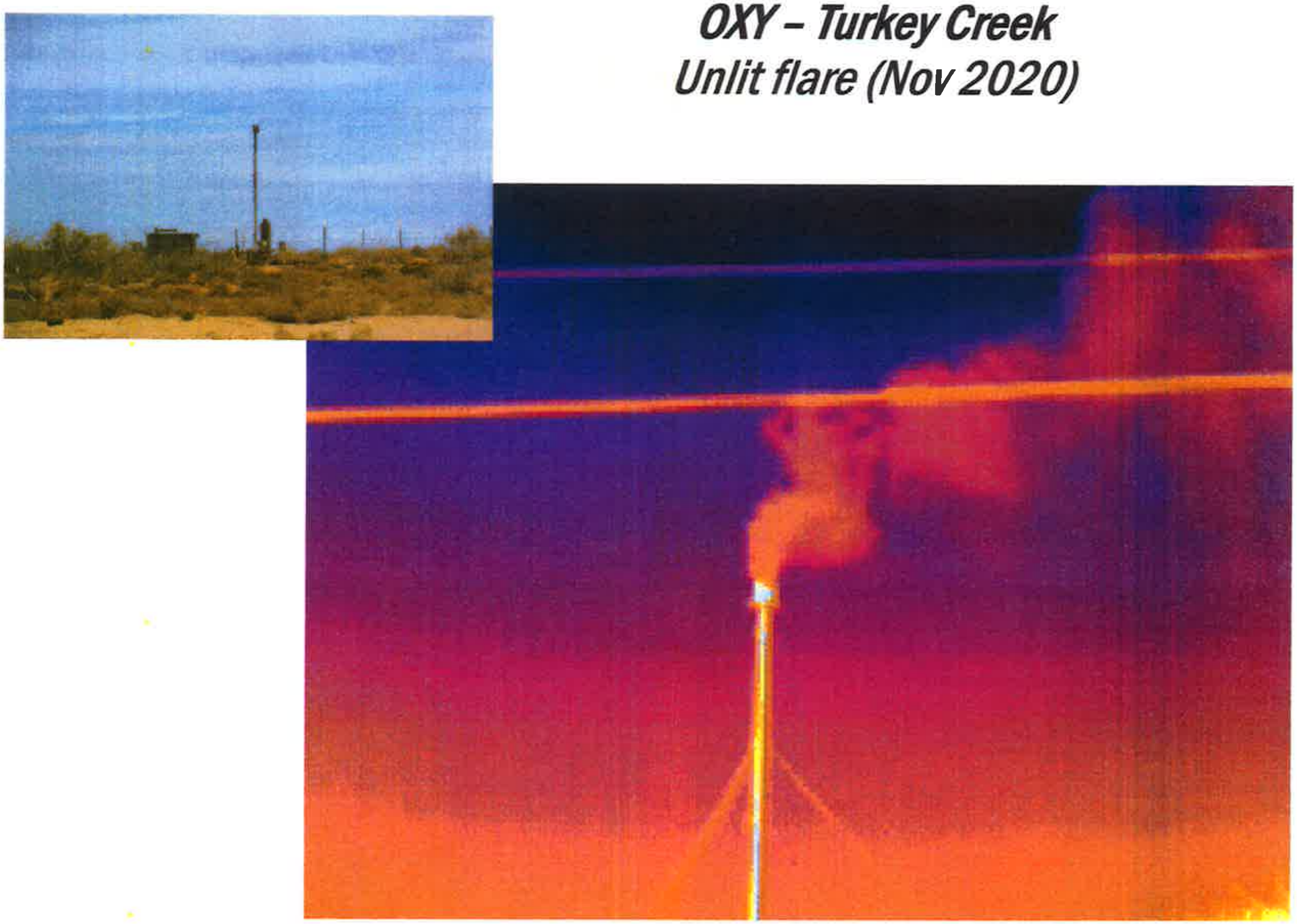
CAUTION
THIS MOTOR STARTS AUTOMATICALLY
DANGER

Apache – AB State 647 #008

Unlit flare (Nov. 2020)



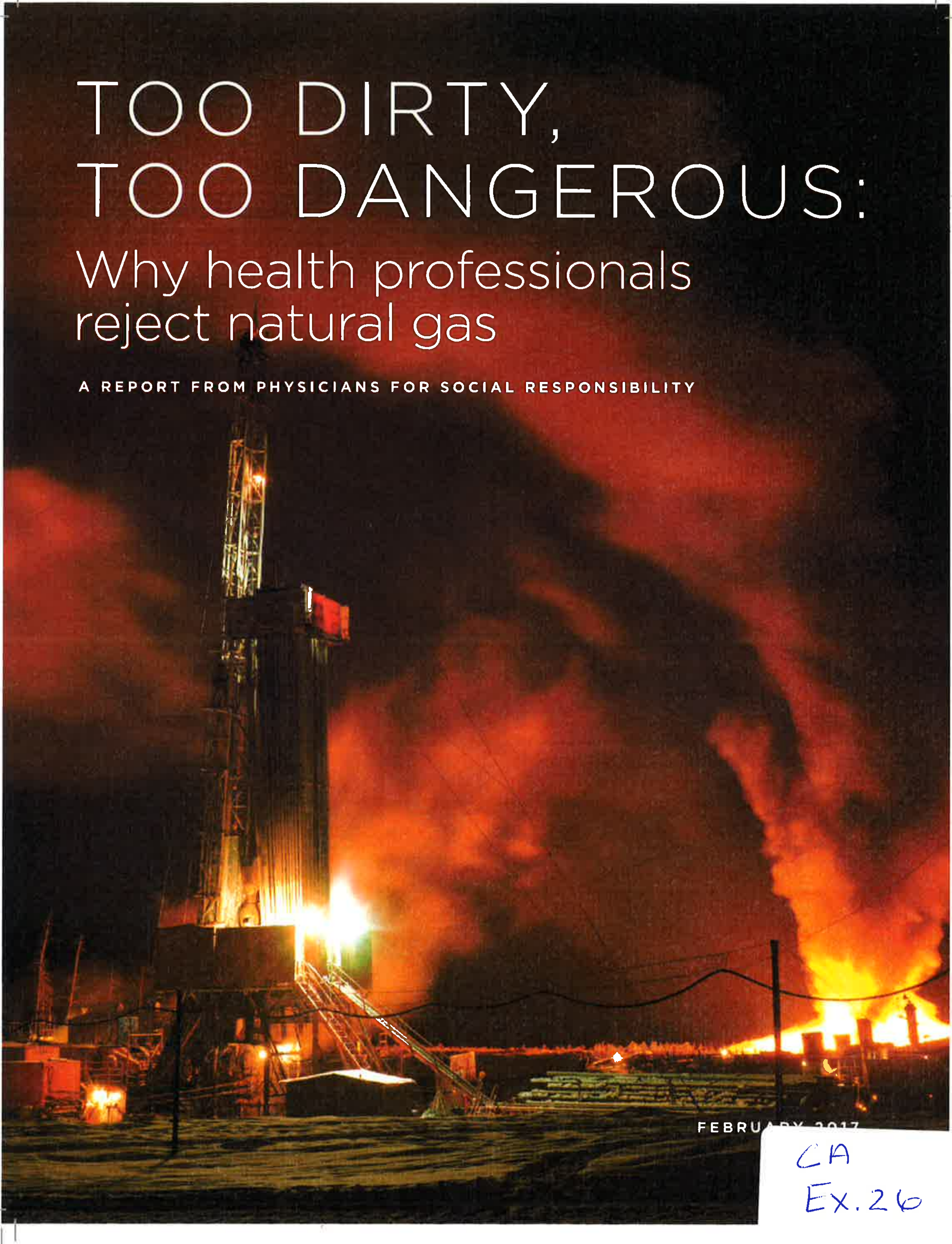
OXY – Turkey Creek
Unlit flare (Nov 2020)



TOO DIRTY, TOO DANGEROUS:

Why health professionals reject natural gas

A REPORT FROM PHYSICIANS FOR SOCIAL RESPONSIBILITY



FEBRUARY 2017

CA
Ex. 26

AUTHORS:

Barbara Gottlieb, with Larysa Dyrszka, MD

ACKNOWLEDGEMENTS:

We thank the many people who contributed to this report. Emily Copeland, Jake Hays, Amy Kostant, Lena Moffitt, Barton Schoenfeld, MD and Catherine Thomasson, MD provided useful comments on the text. PSR interns Casey Crandell, Shirley Kawafuchi and Ryan Miller assisted with research and updating. However, any errors are the responsibility of the authors. We also thank the Sierra Club for their kind support of production and printing.

Too Dirty, Too Dangerous: Why Health Professionals Reject Natural Gas

A REPORT FROM PHYSICIANS FOR SOCIAL RESPONSIBILITY

Fracking can cause water and air pollution and extensive leakage of methane into the atmosphere.

PHOTO: David R. Tribble

EXECUTIVE SUMMARY

There are compelling reasons to question the use of natural gas (methane), given the risks it poses to human health. This report summarizes recent scientific findings that document methane's implications for health.

Methane extraction, especially by means of high-volume horizontal hydraulic fracturing (fracking), releases methane and dangerous toxic substances into the water and air. So do the subsequent processing, transport and delivery of methane. We classify the associated health threats into two broad categories: those caused by exposure to toxic substances, and those associated with methane's effects on the climate.

TOXIC EXPOSURES

A. WATER CONTAMINATION

In fracking, a complex mixture of chemicals is combined with millions of gallons of water, then pumped deep underground under high pressure to fracture rock, thus releasing tiny bubbles of gas or oil. The list of chemicals used in fracking fluids is considered proprietary business information and is not always made public. However, some fracking fluids contain benzene (known to cause leukemia and other blood cancers), formaldehyde (a known carcinogen), and petroleum distillate (toxins which would render water undrinkable). Where people are exposed to fracking fluids but disclosure of the chemicals involved is not required, health professionals may have to guess at toxicity, thus complicating or delaying treatment.

Some of the chemical-water fracking mixture routinely remains underground, where it can migrate into underground water supplies; methane and fracking chemicals have been found in drinking-water wells near fracking sites. The fracking wastewater that is removed from the well is generally so severely contaminated that conventional water treatment facilities cannot purify it. Its disposal poses a host of new problems, from ground and water contamination to earthquakes.

B. AIR CONTAMINATION

Fracking releases toxic substances not only into the water but also into the air. One of the most dangerous is particulate matter, which causes or contributes to lung diseases like COPD and lung cancer, heart effects including heart attack and congestive heart failure, and ischemic stroke. Fracking also releases volatile organic compounds (VOC's) such as benzene and formaldehyde, both of which are known carcinogens; toluene, associated with mental disabilities and abnormal growth in children, as well as damage to the kidney, liver, and immune and reproductive systems; and xylene, which can affect the nervous system, kidneys, lungs and heart. VOC's also contribute to ground-level ozone, a pollutant that can reduce lung function and worsen bronchitis, emphysema and asthma. Radioactive substances like radon can accompany methane; radon is a potent cause of lung cancer. The full list of dangerous substances is far longer. Because fracking is conducted in rural, suburban and even urban areas, it exposes over 15 million Americans to the toxic substances used in and around drilling sites.

Some of these health risks are not limited to the fracking site. The pipelines and compressor stations that transport fracked gas hundreds of miles from well sites can leak, exposing distant populations to dangerous substances that travel through the pipelines along with the methane; these include, notably, particulate matter, volatile organic compounds, and radon and its radioactive decay products. This infrastructure also carries the risk of explosions and intense fires.

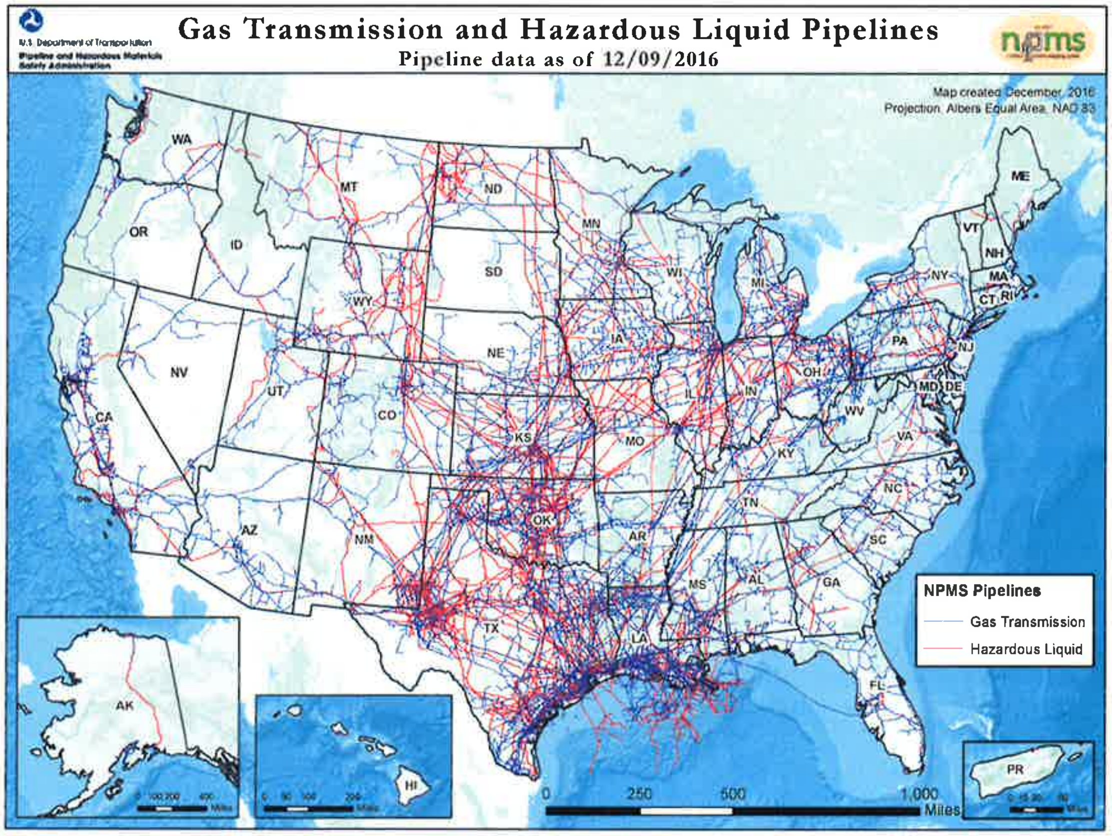
C. HEALTH OUTCOMES

The risks from exposure to fracking-related toxics are not theoretical. Evidence is accumulating that exposure to fracking-related substances has caused serious health effects. Proximity to fracking sites has been shown to be associated with an increase in various health symptoms. Some, such as migraine headaches, severe fatigue and nosebleeds, may indicate underlying health impacts whose causes and implications may not be fully understood. Research indicates certain health outcomes associated with proximity to fracking sites are immediately understood to be serious; these include the increase in high-risk pregnancies, birth defects and premature births. (Premature birth is a leading cause of infant death.) Other health outcomes may not manifest for years, given their long latency periods, but peer-reviewed research shows a clear link between early life exposures to some of the chemicals used in fracking and eventual adverse health effects. Evidence also links fracking to effects on farm animals, including stillbirths and deaths. Fracking's impact on the food supply is not yet known.

FRACKING AND CLIMATE CHANGE

A. CLIMATE IMPACTS ON HEALTH

Methane is an extremely potent climate change gas, 86 times more potent than carbon dioxide over its first 20 years in the atmosphere. As such, it contributes to the host of threats to health known to be associated with climate change here and around the world. These include heat waves, which are the most lethal impact of climate



change in the United States; the spread of diseases carried by insects and other vectors, such as West Nile disease, malaria, and Lyme disease; intense hurricanes, storms, and sea level rise; flooding, which may cause water contamination and destruction of homes and crops; and droughts, wildfires, and decreased crop yields.

B. LEAKAGE AND TIPPING POINTS

Methane leakage into the atmosphere is a problem whose magnitude is now being reassessed: Rates of leakage appear significantly higher than was previously calculated, especially from fracked wells, both active and abandoned; infrastructure including compressor stations; and pipelines, including distribution pipelines for heating and cooking. Large storage facilities, such as Aliso Canyon in California, have emerged as another source of methane leakage. The cumulative impact of this leakage may overwhelm the apparent climate advantage of burning methane gas instead of coal for power generation.

Due to tipping points in the climate system, the next 20-30 years will be decisive in determining the extent of climate change impacts. With air and ocean temperatures rising worldwide, we are in danger of surpassing the critical threshold of a greater than 2º C temperature increase. If that happens, much of the world's permafrost will melt. The result: vast amounts of carbon dioxide and methane will be released, yielding even greater climate change acceleration; more parts of the world would reach unlivable temperatures. The critical need to avoid such a climate crisis requires that we take into account methane's near-term warming impacts and act expeditiously.

CONCLUSIONS

Our nation's policies and practices must recognize and respond to these grave health hazards. Industry and government action to stem methane leaks are welcome steps in the right direction but are inadequate: they reduce but do not resolve methane leakage and toxic threats. Therefore, Physicians for Social Responsibility calls for a full and honest assessment of methane gas's impacts on health, including the following steps to protect human health:

- Calculate methane's climate-forcing potential based on its impact over its first twenty years in the atmosphere;
- Develop a thorough inventory of methane gas leakage across its entire lifecycle; and
- Appraise the toxic risks associated with methane, including at the points of extraction, processing, transport and distribution.
- Ensure that natural gas projects are subject to fundamental health-protective policy, including the Clean Water Act, Clean Air Act, and the Resource Conservation and Recovery Act.
- Require companies conducting hydraulic fracturing to fully and transparently declare the chemicals they use in those processes.
- Require federal, state and local governments to prioritize the protection of human health in their decisions concerning gas-related projects.

These factors should inform public policy and should lead to the phasing-out of methane gas.

Finally, to meet our nation's need for abundant energy, PSR calls for a swift and equitable transition to the production and deployment of energy efficiency and virtually carbon-free renewable energy sources including solar, wind and geothermal power. Our health and that of future generations deserve and depend on a clean energy future.

Fracking can cause water and air pollution and extensive leakage of methane into the atmosphere.

PHOTO: EcoFlight

METHANE GAS ACCELERATES CLIMATE DISASTER

What should be the role of natural gas in our nation's energy mix, given the need to reduce greenhouse gas emissions? How severely does natural gas impact the climate? What are its other effects on human health? These questions are at the heart of an active debate that has grown more urgent as coal-fired power plants are retired. The answers that are emerging indicate that we must reassess the value of natural gas as a fuel—especially as U.S. methane emissions have increased by more than 30 percent over the past decade[1] and methane has overtaken coal as the most-used fuel in electricity production.[2]

METHANE, A MAJOR GREENHOUSE GAS

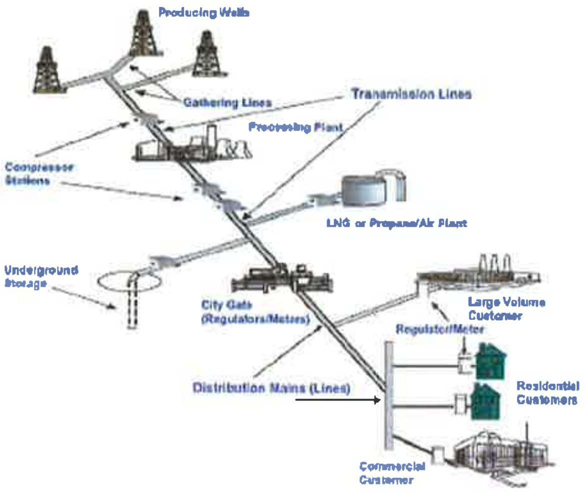
Climate scientists know that the burning of fossil fuels is driving much of the increase in global temperatures over the past 65 years.[3] About a third of the greenhouse gases propelling that increase come from burning coal to produce electricity. Natural gas, whose primary ingredient is methane, is often proposed as an alternative to coal, since when burned it emits only about half as much carbon dioxide.[4] But that comparison holds true only at the point of combustion. Due to leaking methane, which escapes across the natural gas supply chain from the well head to the end user, natural gas's effect on the climate is greater, perhaps much greater. That's because while it is in the atmosphere, methane has a much stronger heat-retaining impact than carbon dioxide. And while a methane molecule lasts only 12.4 years in the atmosphere, it breaks down into carbon dioxide (CO_2) and water vapor, and those greenhouse gases extend methane's impact on the climate for decades. Over a 20-year timeframe, methane is 86 times more potent at trapping heat than CO_2, according to the IPCC.[5]

Those 20 years are an appropriate timeframe to consider, given that it is roughly the window of opportunity that remains for us to slow climate change. If we don't contain greenhouse gas levels in the coming years, we are likely to see world temperatures increase more than 1.5°C to 2°C above preindustrial levels, the limit the U.S. and most of the world's nations agreed to in the 2015 Paris Accords. Increases beyond those levels are likely to melt much of the world's permafrost,[6] releasing such vast quantities of stored methane and carbon dioxide that the world would experience climate change irreversible on a human time scale.[5, 7] The critical need to avoid that tipping point requires that we assess natural gas's powerful impact on our climate, including the impacts of leakage from natural gas facilities, and act appropriately.

METHANE LEAKAGE FROM NATURAL GAS EXTRACTION

A growing body of scientific evidence shows that methane leaks into the atmosphere during every phase of the natural gas supply chain: from drilling sites, processing, transport, storage and final distribution. The rate of that methane leakage is hotly debated. A 2016 study found that researchers' estimates of leaks across the supply chain ranged from 0.2 to 10 percent of produced methane,[8] with the variation due in part to inherent difficulties in measuring leaks.

The most precise measurements are taken when scientists can go directly to the field (well sites, drilling and processing equipment, pipelines or other pieces of infrastructure) and measure the methane leakage, then extrapolate from an average of those measurements. These "bottom-up" studies have high internal validity, that is, the data are generally accurate for the sites where they are taken. However they lack corresponding high external validity, meaning that generalizing those results is not reliable; for example, a relatively small database of samples is likely to under-represent infrequent but high-emission events such as venting and accidental leaks (or by the same token, the infrequent low-emitting, ideally managed well site). However, developing a large and statistically random database is difficult: site-by-site data collection is labor-intensive and time-consuming; access to fracking sites is often restricted, whether by the drilling company or the land owner; and databases are likely to miss the numerous small leaks that have been found to occur in the natural gas system far downstream from well sites.



Natural gas industry, from production through distribution.
SOURCE: EPA

Another means of estimating leakage rates, referred to as "top-down," measures methane in the

Fracking often introduces heavy industrial activity, and pollution, into rural areas.
PHOTO: U.S. Geological Survey.

atmosphere, using collection tools placed on towers, airplanes, or on cars doing drive-by surveys where oil and gas extraction and processing are occurring. Scientists then interpret the resulting data in light of other data gathered (wind patterns, industry operation levels, other sources of methane release such as agriculture, etc.) to model how much methane is attributable to oil and natural gas sector activity. These modeling-based studies are considered to have high external validity, that is, their results can more readily be generalized to other fracking sites. However they have lower internal validity, in that multiple other factors can affect atmospheric methane levels, making it difficult to say that no other variables contributed to the result.

A ground-breaking study of natural gas leakage from production sites, conducted by a consortium that included the National Oceanographic and Atmospheric Administration, the Environmental Defense Fund, nine universities and two private entities, succeeded in 2015 in reconciling top-down (atmospheric) and bottom-up (source-specific) estimates of methane leakage. That study, which examined the Barnett Shale oil- and gas-producing region of Texas, one of the nation's major natural gas production areas, used aircraft to capture atmospheric samples from production, processing, and distribution sources. It concluded among other things that methane emissions from oil and gas operations exceeded those reported by government inventories, showing results fully 90 percent higher than estimates based on the U.S. Environmental Protection Agency (EPA)'s Greenhouse Gas Inventory.[9]

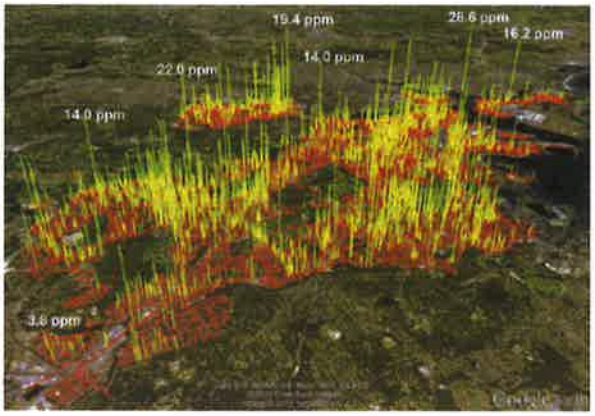
Active well sites are not the only source of leakage; methane also escapes from abandoned wells. Neither the EPA nor any equivalent state agency monitors methane leaking from abandoned wells,[10] yet studies indicate that three million abandoned wells exist[11] and that their leakage rates increase with age. A study conducted by an oil and gas company found that about five percent of natural gas wells leaked immediately; 50 percent were leaking after 15 years, and 60 percent after about 30 years.[12] As the wells constructed in the recent fracking boom begin to age, they will continue to add to global warming.

Flaring of methane from a fracking well.

How high, then, is the level of methane leakage from production sites? A 2014 study used satellite data to quantify fugitive emissions from the Bakken and Eagle Ford shale formations; it estimated their leakage rates at roughly 10.1 and 9.1 percent respectively. The study noted that those rates of leakage "call... into question" the climate benefit of natural gas use.[13]

METHANE LEAKAGE FROM INFRASTRUCTURE

Methane leakage also occurs across the natural gas supply chain, including processing, transport, storage facilities and final distribution. Gas escapes from the processing plants that remove impurities and from the compressors that pressurize the pipes to keep gas flowing; in fact, a study in Texas' Barnett Shale found that methane emissions from compressor stations were substantially higher than from well pads.[14] Another study of the Barnett Shale found methane emissions from natural gas processing plants and a compressor



Methane leaks in the city of Boston, shown as concentrations (in parts per million) SOURCE: Reprinted from Environmental Pollution, Vol 173, Nathan G. Phillips et al., Mapping urban pipeline leaks: Methane leaks across Boston, 1-4, Copyright (2013), with permission from Elsevier.

station in the field were 3.2 to 5.8 times higher than estimates based on the U.S. EPA Greenhouse Gas Reporting Program, where large-scale industry sources are required to self-report emissions.[15]

Natural gas also leaks from pipelines. According to a report by the EPA's Office of Inspector General, the EPA acknowledged in 2012 that pipeline leaks "accounted for more than 13 million metric tons of carbon dioxide equivalent emissions"—at that time, more than 10 percent of total methane emissions from natural gas systems in the U.S.[16] Scientists measured methane leakage from distribution pipes under the streets of Boston and noted in January 2016 that of 100 natural gas leaks surveyed, 15 percent qualified as "potentially explosive," adding, "All leaks must be addressed, as even small leaks cannot be disregarded as 'safely leaking.'"[17] A study conducted in the Boston area in 2015 found that methane emissions from distribution pipelines and end use were two to three times greater than had been predicted by existing inventory methodologies and industry reports. The authors noted that areas that consume natural gas, as distinct from those that produce it, "may...represent areas of significant resource loss" and that the many leaks present in the Boston area "contribute[d] significantly to the total CH_4 source."[18] The same study of "downstream" methane emissions in Boston (transmission, distribution and end use) found that gas escaped at an average loss rate between 2.1 and 3.3 percent—more than twice as high as inventory data suggested.

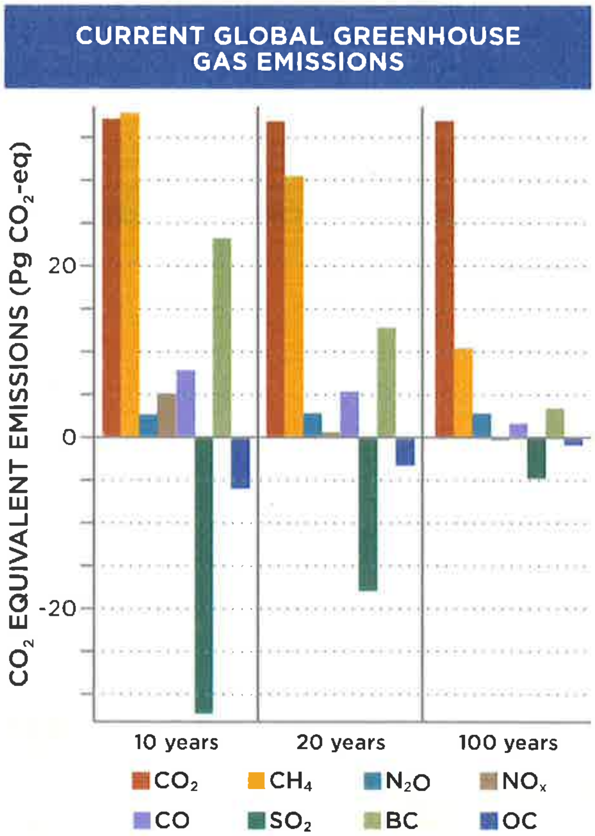
Finally, natural gas storage facilities have proven also to leak. A massive leak at the Aliso Canyon natural gas storage facility near Los Angeles, California remained uncontrolled between October 2015 and February 2016, emitting more

Permafrost thawing in the Artic Circle. PHOTO: Brocken Inaglory than 100,000 tons of methane into the air[19] — an amount estimated to equal the annual greenhouse gas emissions from over half a million cars.[20] It was the worst methane leak in U.S. history[21] and created a plume detectable from outer space.[22] In response, Congress passed the first federal legislation requiring regulation of underground natural gas storage facilities. It obligates the Pipeline and Hazardous Materials Safety Administration to develop regulations for gas storage facility construction and operation.[23]

HOW MUCH LEAKAGE OVERALL?

While the rate of methane leakage continues to be debated, the trend in research findings points to higher, not lower, rates of leakage. Earlier studies estimated that as little as 1.2 percent of the total methane output generated by the natural gas industry leaked into the atmosphere, with EPA and industry findings generally falling on the low side of the leakage rate spectrum. This however was widely disputed, with the EPA's own inspector general stating in 2014 that the EPA had not placed enough focus on the issue and was using outdated information in its analyses.[24] The EPA later revised upwards its estimates of 2014 life cycle methane emissions from the oil and gas industry, considered together, by 34 percent.[25] A 2016 study by Cornell University researcher Robert Howarth, calculating that transport, storage, and distribution systems added a 2.5 percent emission rate to the leakage at the point of extraction, concluded that on average 12 percent of the methane produced by fracking is lost by leaking into the atmosphere.[26]

How much methane leakage can the planet absorb without driving us to the tipping point? It was estimated in 2012 that the climate benefit of switching from coal-fired to gas-fired power plants can be achieved only if total natural gas leakage is below a threshold of 3.2 percent.[27] Howarth in 2014 proposed a comparable if slightly lower threshold of below 2.4 to 3.2 percent leakage.[28] To achieve those rates, the natural gas industry would have to attain far greater levels of methane capture, leak repair, and phase-out of blowdowns, flaring and other methane-emitting techniques than are now practiced.


CURRENT GLOBAL GREENHOUSE GAS EMISSIONS

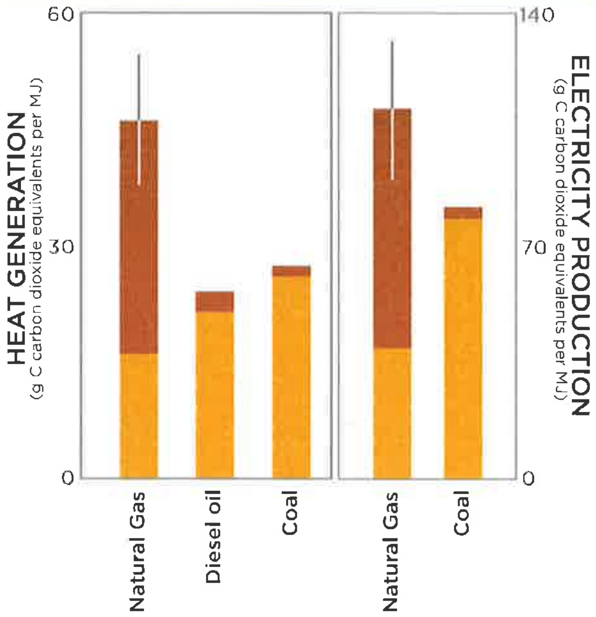
Current global greenhouse gas emissions, as estimated by the IPCC, weighted for three different global warming potentials and expressed as carbon dioxide equivalents. At the 10-year time frame, global methane emissions expressed as carbon dioxide equivalents actually exceed the carbon dioxide emissions.
SOURCE: IPPC

Whether that can be achieved remains to be seen. One study, based on data and commentary from oil and gas producers and other industry sources, suggests that as much as 40 percent of fugitive emissions could be halted at minimal cost.[29] The EPA for its part in 2016 introduced regulations to reduce methane leaks from new, modified or reconstructed natural gas operations; it planned to propose similar regulations for existing sources in 2017. However, the new political environment places in doubt further regulation of the gas and oil industry. And even the Obama Administration's goal of cutting methane emissions from the industry by 40 to 45 percent[30] might not have been sufficient. Too little is known about actual leakage levels and their implications. How much methane leaks: 9.3 percent? 12 percent? How great is the actual level of methane production going to be? And how low do leakage rates need to be? A 40 percent reduction in a 12 percent industry leakage rate may not be sufficient for climate safety.

NATURAL GAS OR COAL?

What do these numbers imply about the climate benefits of replacing coal with natural gas to generate electricity? Scientists disagree. Two 2011 studies concluded that "the substitution of gas for coal as an energy source results in increased rather than decreased global warming for many decades..."[31] and that, "Compared to coal, the footprint of shale gas is at least 20 percent greater and perhaps more than twice as great on the 20-year horizon" and over a 100-year timeframe, comparable to coal.[32] A 2014 study found that over the 40-year lifespan of a power plant, assuming equally efficient plants and a low 2 percent methane leakage rate, methane and coal were roughly equal in their greenhouse emissions. Even methane leakage rates of 5 or 6 percent could be offset by using a most-efficient (60 percent) gas-burning power plant versus a merely typically efficient (34.3 percent) coal plant. Over a 100-year timespan, because of methane breakdown in the atmosphere, the study found that the warming effect from coal-fired plants would "considerably exceed" that of natural gas plants, even if methane leaks reached 9 percent.[33] However, another study conducted the same year concluded that turning to natural gas would have little to no effect in reducing greenhouse gas emissions and might actually increase them. Based on simulations from five integrated assessment models, it found that a majority of the models actually reported a small increase in climate-warming effects associated with the increased use of abundant gas.[34] **In short, the comparison is complex, the timeframe matters, and consensus does not exist in the scientific community. But there is a larger point that needs to be made: Both of these fossil fuels increase climate change and harm human health. To protect health and for the wellbeing of society, we need to transition our energy system off both of them.**

COMPARISON OF GREENHOUSE GAS FOOTPRINTS



Comparison of the greenhouse gas footprint for using natural gas, diesel oil, and coal for generating primary heat (left) and for using natural gas and coal for generating electricity (right).

Methane leakage is not the only factor that determines natural gas's contribution to climate change; the duration of our dependence on fossil fuels also needs to be considered. If natural gas replaces coal in electricity generation, then power plants will be built or converted that are likely to operate for 40 years. This would extend our use of fossil fuels — and thus our climate-damaging emissions — far beyond the point of sustainability. Not only that; "the expansion of natural gas risks a delay in the introduction of near-zero emission energy systems,"[35] reducing the market for renewable energy sources like wind and solar power, which emit virtually no greenhouse gases beyond the limited energy required for production and transportation. Thus the choices that we make today about whether to pursue or reject natural gas are, implicitly, choices about when and how quickly we transform our energy system from fossil fuels to cleaner, healthier renewable energy and energy efficiency.

CLIMATE CHANGE EFFECTS ON HUMAN HEALTH

Climate change damages human health and well-being in many ways. These health impacts have been widely studied and documented, including multiple climate-related threats that are specific to the United States. Below is a summary of health threats from climate change that are anticipated to strike the United States, drawn from the 2014 "National Climate Assessment" conducted by the U.S. Global Change Research Program.[36]

CLIMATE CHANGE FACTORS	RESULTS	POTENTIAL HEALTH EFFECTS
EXTREME HEAT EVENTS	Heat waves.	Deaths from heat stroke and related conditions, cardiovascular disease, respiratory disease, and cerebrovascular disease. Increased hospital admissions for cardiovascular, kidney, and respiratory disorders.
HEAT, WILDFIRES, AIR STAGNATION	Air pollution: heat + certain chemicals in the atmosphere yield increased ground-level ozone; wildfires and air stagnation episodes increase particulate matter.	Diminished lung function, increased hospital admissions and emergency room visits for asthma, and increases in premature deaths.
MORE FROST-FREE DAYS, WARMER AIR TEMPERATURES	Increased CO_2 yields higher pollen concentrations, longer pollen seasons.	Increased allergic sensitizations and asthma episodes, loss of work and school days. Harder to control asthma.
EXTREME RAINFALL, RISING TEMPERATURES	Growth of indoor fungi and molds.	Increases in respiratory and asthma-related conditions.
RECORD HIGH TEMPERATURES INCREASE VULNERABILITY OF FORESTS TO WILDFIRE.	Higher air pollution, including particulate matter, carbon monoxide, nitrogen oxides, volatile organic compounds (ozone precursors).	More respiratory and cardiovascular hospitalizations, emergency department visits, medications dispensed for asthma, bronchitis, chest pain, chronic obstructive pulmonary disease (COPD), respiratory infections. Deaths.

CLIMATE CHANGE FACTORS	RESULTS	POTENTIAL HEALTH EFFECTS
HEAVY RAINFALL	Floods	Deaths, mostly due to drowning
	Floods carry disease agents	Waterborne disease outbreaks
	Water intrusion into buildings can increase mold	Asthma, coughing and wheezing, lower respiratory tract infections such as pneumonia
DROUGHT	Wildfires, dust storms, extreme heat events, flash flooding, degraded water quality, and reduced water quantity	Degraded air quality (see above); also, increased incidence of Valley fever. Flooding (see above).
WEATHER VARIABLES SUCH AS TEMPERATURE CHANGES	Weather variables can change the geographic range of disease hosts (vectors)	Possible exposure to vector-borne diseases including Lyme, dengue fever, West Nile virus, Rocky Mountain spotted fever, plague, and tularemia. Vector-borne diseases not currently found in the United States, such as chikungunya, Chagas disease, and Rift Valley fever, can also become threats.
EXTREME RAINFALL EVENTS, EXTREMELY LOW PRECIPITATION, HIGHER AIR AND WATER TEMPERATURES	Favorable conditions for the growth of pathogens of food-borne and water-borne diarrheal disease; increased human exposure.	Diarrheal diseases including Salmonellosis and Campylobacteriosis
COMBINED EFFECTS OF CHANGES IN RAINFALL, SEVERE WEATHER EVENTS, AND INCREASING TEMPERATURES	Some crop yields will decline, as will livestock and fish production. Decreased protein in crops such as barley, sorghum, and soy. Increases in weeds and crop pests may lead to greater use of insecticides, herbicides.	Food insecurity for groups with particular dietary patterns like Alaska Natives and for low-income people. Loss of nutrition. Increased exposure to toxic agricultural products.
EXTREME WEATHER (e.g. hurricanes, floods, heat waves, wildfires)	Abnormal events increase mental health and stress-related disorders.	High levels of anxiety and post-traumatic stress disorder. Adverse birth outcomes including preterm birth, low birth weight, and maternal complications. Increases in suicide rates.

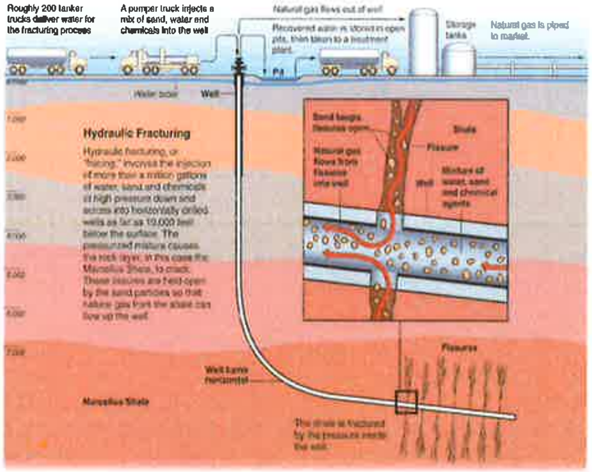
HEALTH EFFECTS OF HYDRAULIC FRACTURING (FRACKING)

Fracking* is a technique for extracting natural gas from deep underground bands of shale or other porous rock. Designed to extract previously untapped gas reserves, it involves pumping a highly pressurized mixture of chemicals and water deep into the earth to fracture the underlying rock formations. Many of the chemicals associated with fracking cause cancer, are endocrine-disruptive, or are otherwise toxic.[37]

The natural gas boom of the past 15 years is unprecedented, bringing over 15 million Americans into close proximity with this heavy industry[38] and resulting in increased human exposure to toxic substances. A growing body of scientific evidence links fracking to health effects ranging from headaches and nosebleeds to asthma exacerbations, birth defects and premature births. More than 900 peer-reviewed publications[39, 40] provide evidence of environmental, health, and societal effects of fracking.

FRACKING, HEALTH, AND AIRBORNE EMISSIONS

Fracking operations release toxic gases, including proven human carcinogens and potent toxicants of the nervous system. Among the most dangerous gases are certain volatile organic compounds (VOCs), which are released at each stage of fracking, from extraction to delivery.[41] VOCs commonly associated with fracking operations include the BTEX complex (benzene, toluene, ethylbenzene and xylene), which can cause cancer, affect the nervous system, or cause birth defects. (See chart.) A study by the University of Colorado Denver School of Public Health documented dangerous airborne levels of benzene near hydraulic fracturing operations as well as elevated risks of cancer for residents living within a half-mile of a



Hydraulic Fracking. ILLUSTRATION: Al Granberg

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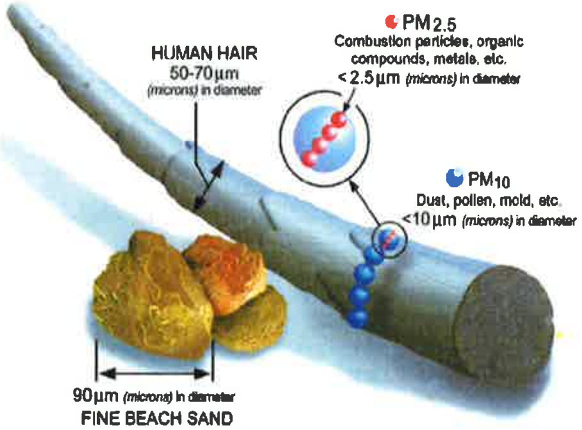
* Subsequent to this reference, we will use the term "fracking" to refer both to the process of fracturing the rock formations and to the associated operations that extract, process and transport natural gas. This encompasses land clearing, well drilling, construction of the well casing, flaring, wastewater extraction and storage, processing, compression, disposal of wastes, and natural gas transportation and distribution.

drilling site.[42] Ambient air testing near gas drilling operations in northern Texas found excessive amounts of benzene and of carbon disulfide, an extremely high-risk pollutant with "disaster potential" as categorized by the Texas Commission on Environmental Quality.[43]

In addition to being toxic, VOCs form ground-level ozone, also known as smog, when they mix with the nitrogen oxides from diesel-fueled trucks and equipment at fracking sites. Exposure to ground-level ozone can cause irreversible damage to the lungs[44] and significantly increase the chance of premature death.[45] VOCs and ozone pollution have been detected at dangerous levels at fracking sites, even in rural areas not usually associated with air pollution. Uintah County, Utah, home to one of the highest-producing oil and gas fields in the U.S., has experienced dangerously high levels of VOCs and ozone.[46] For parts of 2011, the level of ozone pollution in rural Wyoming's gas drilling areas exceeded that of Los Angeles and other major cities.[47]

Another study identified significant amounts of over 40 harmful chemicals in the air near drilling sites in Colorado.[48] While none were detected at levels above EPA limits, that study and others have noted that the EPA's ambient air quality standards may not be strict enough.[49] They do not fully account for long-term health effects of chemicals,[50] for the risks of episodic spikes in contaminant levels,[51] or for the enhanced risks to espe-



Relative sizes of particulate matter. ILLUSTRATION: EPA

AIR CONTAMINANTS ASSOCIATED WITH HYDRAULIC FRACTURING

BENZENE	Known carcinogen. May cause anemia; can lessen white blood cell count, weakening the immune system.[58] Prolonged exposure may result in leukemia, reproductive and developmental disorders, and other cancers.[59] There is no known safe level for air exposure.[60]
TOLUENE	Long-term exposure may affect the nervous system and cause miscarriages and birth defects.[61]
ETHYL-BENZENE	Long-term exposure may result in blood disorders.[62]
XYLENES	Short-term exposure to high levels may cause irritation of the nose and throat, nausea, vomiting, and neurological effects. Long-term exposure at high levels may affect the nervous system.[63]
NITROGEN OXIDES	Decrease oxygen absorption and weakens the lungs. Short-term exposure aggravates asthma. Contribute to the formation of ground-level ozone and particulate matter.[64] [65]
METHANE, ETHANE, PROPANE	May cause rapid breathing and heart rate, clumsiness, emotional upset. At greater exposure, may cause vomiting, collapse, convulsions, coma and death.[66]
FORMALDEHYDE	A known carcinogen.[67] Can cause permanent and irreversible damage to the lungs.
SULFUR DIOXIDE	A major contributor to acid rain.[68] Can cause coughing, wheezing and shortness of breath and worsen asthma[69] and destabilize heart rhythms.[70] It is linked to bronchial reactions, reduced lung function and premature death.[71]

Three Brothers Compressor Station, Marcellus Shale, Atlasburg, Pennsylvania. PHOTO: MarcellusAir

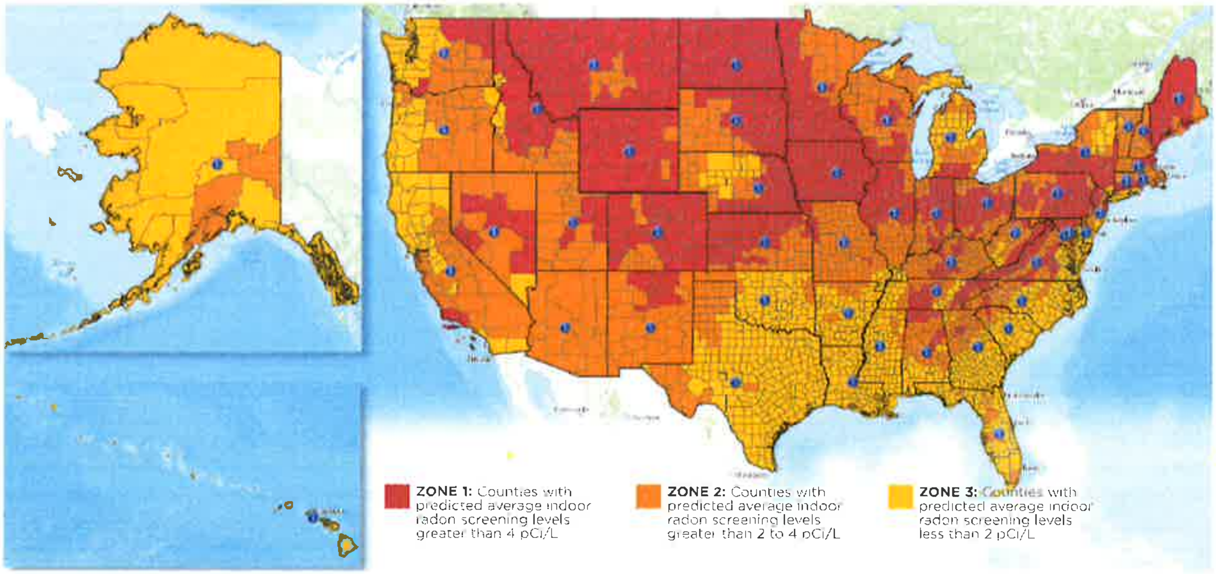
cially sensitive populations,[52] such as pregnant women, young children and the elderly.

Particulate matter is another fracking-related health hazard. Particulate matter is generated by the thousands of truck trips necessary for transporting fracking materials and the diesel motors operated on fracking sites and in many compressor stations. Studies have shown that inhalation of particulate pollution causes decreased lung function, aggravated asthma symptoms, nonfatal heart attacks, and high blood pressure.[53] Long-term repeated exposure is associated with cardiovascular disease and death.[54] Children are particularly vulnerable to particulate pollution; they may suffer decreased lung function, worsening asthma symptoms, and chronic bronchitis.[55] Rates of preterm births, low birth weight, and infant mortality are higher in communities with high particulate levels.[56] Exposure to particulate matter is also associated with increased school absences, emergency room visits and hospital admissions.[57]

Fracking for natural gas may also bring radioactive substances to the surface.[72] Some shale formations — notably the Marcellus — contain large amounts of naturally occurring radon gas as well as other radioactive elements. Radon is the leading cause of lung cancer among non-smokers and the second leading cause among smokers; the EPA attributes 21,000 lung cancer deaths per year on a nationwide basis to radon exposure.[73] Radon has a short half-life (3.8 days), but generates radioactive decay products, primarily polonium and lead, with longer half-lives: 22.6 years and 138 days, respectively. Polonium and lead have both been found to accumulate along the interior of natural gas pipes and related infrastructure.[74]

FRACKING, HEALTH, AND WATER CONTAMINATION

Fracking operations consume and contaminate enormous quantities of water. Hydraulic fracturing fluid is highly toxic to human and animal life, as



Radon Map of the United States by county. ILLUSTRATION: EPA "many of the chemicals... should not be ingested at any concentration."[75] According to a 2011 Congressional report, 29 of the known substances most commonly used in fracking are dangerous enough that they would be regulated under the Safe Drinking Water Act or the Clean Air Act, if the 2005 Energy Policy Act had not exempted fracking from these fundamental environmental protection laws.[76] In fracking, these chemicals are mixed with huge quantities of water. In order to fracture a single well site, natural gas companies typically use over four million gallons of water — an amount equivalent to what 11,000 American families use in a day.[77] Such intensive water use places hydraulic fracturing in competition with other consumers of water including households, agriculture, industry, and recreation, and has become an issue in states like California, which is experiencing a historic drought. Nearly half of all fracking operations occur in areas with high or extremely high water stress.

An estimated 20 to 40 percent of water used in fracking subsequently comes back up to the surface, where it is classified as wastewater.[78] Fracking wastewater consists of a mix of withdrawn fracking fluids with naturally occurring brines — waters that contain high levels of salts as well as toxic levels of elements like barium, arsenic and radioactive radium, brought to the surface from deep underground. [79, 80] Oil and gas operations in the U.S. produce more than two billion gallons of fracking wastewater a day, and it is generally so severely contaminated that conventional water treatment facilities cannot purify it.[81] Regardless, fracking wastewater is categorized by the EPA as "special wastes" and as such is exempted from federal hazardous waste regulation under the Resource Conservation and Recovery Act (RCRA). Wastewater spills are a serious problem. The Associated Press (AP) analyzed data from leading oil- and gas-producing states and found that more than 180 million gallons of wastewater spilled in 21,651 incidents over five years (2009-2014).

In California, fracking wastewater from gas and oil extraction is sometimes used to irrigate crops, posing a risk of contamination of groundwater.[82] In addition, the state stores almost 60 percent of its fracking wastewater in unlined open-air pits.[83] Unlined wastewater pits containing oil field (not gas) wastewater in Kern County, in California's agricultural Central Valley, were reported to have contaminated groundwater with salt, boron and chloride.[84] Concerns were raised that these contaminants could eventually make their way into the Kern River, which is used for irrigation and drinking water.

Living close to fracking operations increases the risk of premature birth and congenital heart defects.

More than 95 percent of the nation's fracking wastewater is pumped into an estimated 30,000 injection wells, which serve as permanent storage sites.[85] [86] The U.S. Government Accountability Office (GAO) has found a lack of protection for drinking water sources from fracking injection wells. In 2014, GAO found that both short-term and long-term monitoring were lax, with the EPA neither mandating nor recommending a fixed list of chemicals for states to monitor, and record-keeping varying widely from state to state.[87,88] In Stark County, North Dakota, a newspaper reporter's review of mechanical integrity tests revealed that state fracking waste injection wells were often leaky, and state regulators allowed injection into wells with documented structural problems even though the wells did not meet EPA guidelines for well bore integrity.[89]

Underground injection of large amounts of fracking fluids has been associated with earthquakes, particularly in Ohio[90] and Oklahoma,[91] including a destructive 5.7 magnitude quake in Oklahoma in 2011. A 2015 article in *Science*, the magazine of the American Association for the Advancement of Science, noted that large areas of the U.S. that were "long considered geologically stable with little or no" earthquake activity have become seismically active. The article attributed this to "fluid-injection activities used in modern energy production." [92] The evidence for a causal link between earthquake swarms — repeated earthquakes in a relatively short period of time — and fracking wastewater injection into disposal wells led the Oklahoma Supreme Court to rule unanimously that homeowners can sue the oil and gas industry for injuries or property damage resulting from earthquakes.[93] Evidence now shows that the process of fracking itself can trigger earthquakes.[94]

The risk of drinking water contamination from fracking has been studied by governmental and private researchers. In June 2016, the EPA confirmed in a draft report that drilling and fracking activities had contaminated drinking water.[95] The report documented 457 fracking-related spills over six years; of those, 300 reached an environmental receptor such as surface water or groundwater. University of Texas researchers analyzing 550 water samples from public and private wells found widespread water contamination throughout the heavily drilled Barnett Shale region of northern Texas. Contaminants included elevated levels of benzene and toluene and ten different metals.[96] In a study conducted in northeastern Pennsylvania, methane was detected in 82 percent of drinking water samples, with homes less than one kilometer from natural gas wells exhibiting average concentrations six times higher than those located far away. Ethane and propane were also found in drinking water, again with higher concentrations closer to fracking wells.[97]


Bakken injection site PHOTO: Joshua Doubek

Underground pathways to exposure can occur when hydraulic fracturing pipes carry fracking fluids through aquifers (naturally occurring reserves of underground water). When the cement well casings crack, fracking chemicals can contaminate the aquifer, which may be the sole water source supplying local wells. Such cracks may occur due to age; the Council of Canadian Academies identified the potential for leakage from aging wells as one of its top concerns about fracking. According to one expert panel, "the greatest threat to groundwater is gas leakage from wells from which even existing best practices cannot assure long-term prevention."[98]

DOCUMENTED HEALTH EFFECTS

Recent peer-reviewed medical studies have documented not only health risks, but actual associations between fracking operations and poor health outcomes. For example:

- A study published in *Epidemiology* in March 2016 examined electronic health record data on over 10,000 births in northern and central Pennsylvania. It found that expectant mothers living in the most active fracking areas were at greater risk of high-risk pregnancy and 40 percent more likely to give birth prematurely.[99] Preterm birth is the greatest contributor to infant death and is a leading cause of long-term neurological disabilities in children.[100]
- In a 2014 study of almost 25,000 births, congenital heart defects, and possibly neural tube defects in newborns, were associated with the density and proximity of natural gas wells within a 10-mile radius of mothers' residences in rural Colorado.[101]
- A study by University of Pennsylvania and Columbia University researchers found that fracking for gas and oil in Pennsylvania was associated with increased rates of hospitalization for cardiac, neurological, urological, cancer-related, skin-related problems. In the communities with the most wells, the rate of cardiac hospitalizations was 27 percent higher than in the control county.[102]

Air pollutants from fracking can cause permanent lung damage. Children are particularly vulnerable.

- Research published in the July 2016 *Journal of the American Medical Association* identified a statistical association between progressively worsening asthma symptoms and the patient's proximity to natural gas fracking operations.[103]

Health professionals warn that severe impacts like cancer, chronic respiratory illness, impaired cognition and neurologic impairment may appear in future years, given their long latency periods.[104, 105, 106] Full awareness and documentation of fracking's impacts on health have also been hindered by legal factors. "Gag rules" restrict doctors' rights to share information on patient exposures,[107] nondisclosure agreements are often part of private settlements between farmers and industry,[108] and some gas companies refuse to disclose the identity of chemicals they use in hydraulic fracturing. Laws passed by Congress in 2005 created the so-called "Halliburton loopholes," which exempted oil and gas companies from multiple federal regulations, including those that require monitoring and disclosure of chemicals in air and water.

FRACKING'S IMPACT ON ANIMALS AND AGRICULTURE

A small but growing body of scientific literature indicates that the health of farm animals and wildlife has been harmed by exposure to hydraulic fracturing fluid and air emissions. Animals may suffer higher levels of exposure, as they are outdoors more than humans and drink directly from ponds, streams and puddles. Additionally, their shorter reproductive cycles mean that toxics-induced infertility and other reproductive harms manifest sooner. Animals thus serve as "sentinels" of environmental contamination: if the environment is polluted, then animals may show the effects first.

Veterinarian M. Bamberger and R. E. Oswald, Cornell University professor of molecular medicine, were early investigators of impacts on farm animals. Based on their interviews with farmers near active fracking sites, they have documented stillbirths, near-immediate births and birth defects in cattle exposed to fracking wastes.[109] In an article published in 2012, they studied seven cattle farms in detail and found that "50 percent of the herd, on average, was affected by death and failure of survivors to breed."[110] Other sources have also documented toxic effects of fracking fluid exposures. The Louisiana Department of Environmental Protection recorded a 2009 case of 17 cows dropping dead within hours after drinking spilled hydraulic fracturing fluid.[111] In 2010, 28 cows in Pennsylvania were quarantined after a leaking waste container left a puddle of hydraulic fracking fluid in their field.[112] A year later, the released cows appeared healthy, but gave birth to 11 offspring described as "dead or extremely weak," an outcome that the farm owner called "abominable."[113]

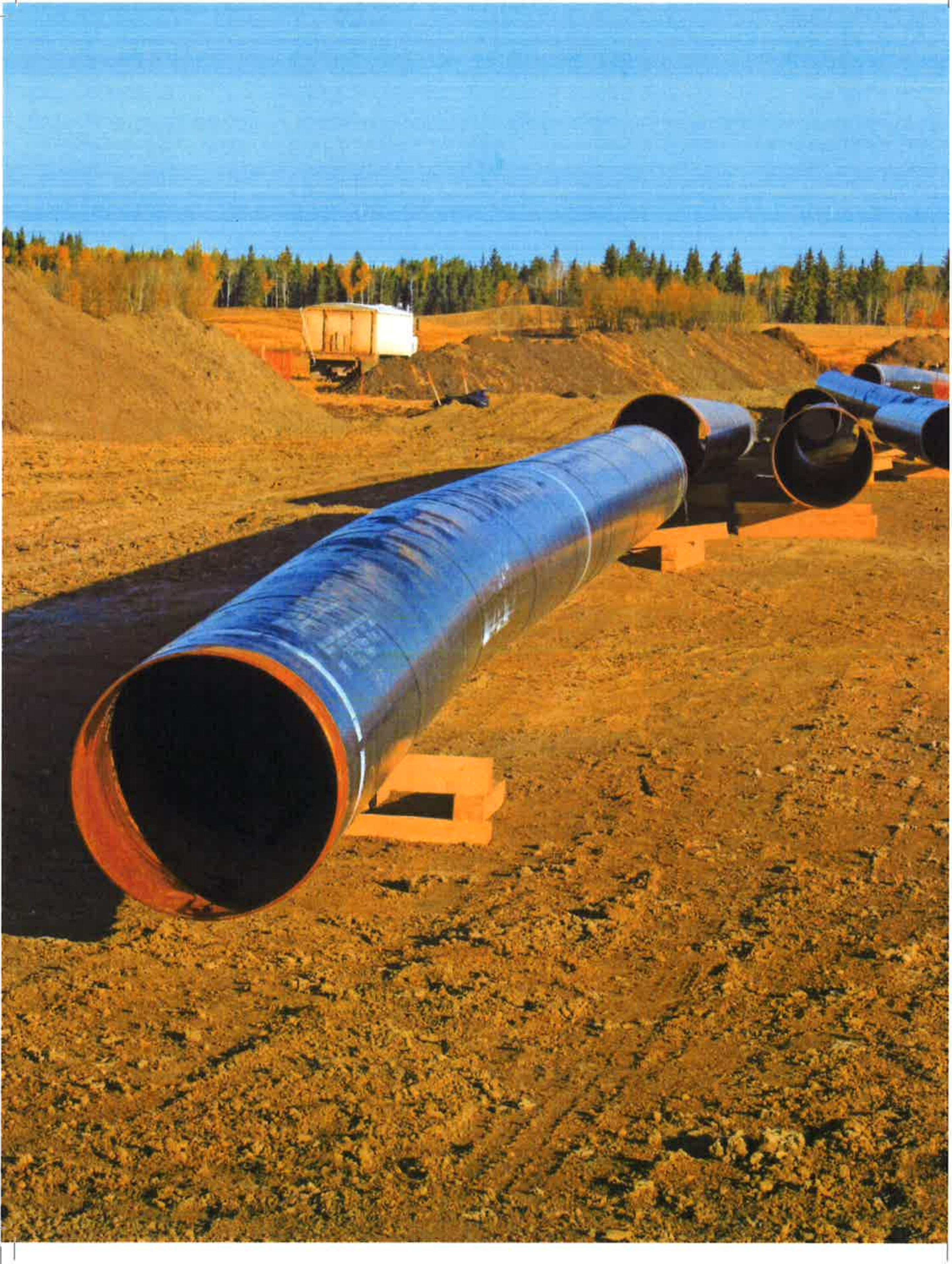
Air pollution associated with fracking sites has also been linked to health risks to farm animals. As early as 2001, thousands of cows in western Canada, one of the original epicenters of fracking, showed significantly increased rates of stillbirth and calf mortality linked to hydrogen sulfide released after natural gas extraction.[114] In Pennsylvania, increased fracking activity has been closely correlated with decreased dairy production.[115] While a direct link is difficult to prove, the correlation illustrates the need for greater caution about, and investigation into, adverse effects of fracking on farm animals.

Wildlife has also been shown to suffer harm from exposure to hydraulic fracturing chemicals. After a Kentucky fracking site spilled hydraulic fracturing fluid into a neighboring creek, "the discharges killed virtually all aquatic wildlife"[116] in the area. Fish that survived the spill developed gill lesions and suffered liver and spleen damage.[117]

The possibility that human health would be affected by consumption of food products from fish or farm animals exposed to fracking toxics is a topic in need of further study. In multiple known cases of chemical exposure, cows continued to produce dairy and meat for human consumption, although those products remained untested for chemical contaminants.[118]

The high-salinity wastewater that accompanies natural gas and oil from fracking wells has also been shown to harm agricultural lands. The Associated Press analysis of wastewater spills included an incident in Fort Stockton, Texas, where the local Groundwater Conservation District fined an energy company $130,000 for illegally dumping 3 million gallons of wastewater in pastures, and another where wastewater from pits seeped beneath a 6,000-acre cotton and nut farm near Bakersfield, California, and contaminated the groundwater. In that case, an oil company was ordered to pay $9 million to the farm owner, who had to remove 2,000 acres from production.[119]

In a field so relatively new, the scientific literature on health effects of fracking is not yet complete. Yet the evidence is substantial that fracking introduces toxic chemicals into the environment and brings up other dangerous substances from deep underground; that these dangerous substances are spread in the air and the water; and that people and farm animals suffer health effects, including birth defects, respiratory and cardiac effects, as a result.



HEALTH EFFECTS OF NATURAL GAS INFRASTRUCTURE

As natural gas is transported from its point of extraction to its point of ultimate use, it travels through an extensive infrastructure system. Gathering pipelines carry the gas to processing facilities, which remove impurities; from there, the gas travels through interstate transmission pipelines, often hundreds of miles, to distribution lines, service lines and end users.

Along the way, compressor stations keep the gas pressurized and moving, while specialized machinery removes water from the gas and cleans unwanted materials out of the pipelines. Storage facilities hold the gas before it is distributed. A growing body of scientific evidence documents leaks of methane, toxic volatile organic compounds and particulate matter throughout this infrastructure. These substances affect health, and the American Medical Association has recognized this by passing a resolution supporting "legislation that would require a comprehensive Health Impact Assessment regarding the health risks that may be associated with natural gas pipelines." [120]

HEALTH RISKS ASSOCIATED WITH PIPELINES

The integrity of transmission pipelines is assessed periodically, but the frequency of those assessments may vary from every seven to every 20 years.[121] In any case, leaks occur. The EPA acknowledged in 2012 that leaks from natural gas pipelines "accounted for more than 13 million metric tons of carbon dioxide equivalent emissions" and represented at that time more than 10 percent of total methane leaks from natural gas systems in the United States.[122] Pipelines may also emit gas during a "blowdown," which involves complete venting of the gases in a pipeline or compressor. Blowdowns are used to control pressure and empty the system and can be accidental or a scheduled part of maintenance. A typical blowdown releases a 90- to 180-foot plume of gas into the atmosphere and can last as long as three hours. Due to their intensity, blowdowns can emit pipeline contents at much higher concentrations than annual emissions data would suggest.[123] Thus, they hold the potential for exposing local residents to greater concentrations of toxic substances than are reflected in the estimates of average exposures which are used in permitting decisions.

Methane leaks have also been documented from the urban pipelines that deliver natural gas to homes and other final users. Besides the "potentially explosive" leaks discovered in the streets of Boston, discussed in section 1,[124] scientists have measured methane leakage from distribution pipes in Washington, DC, where they mapped 5,893 leaks across 1,500 miles of road.[125] As is the case with blowdowns, toxic substances can escape from the pipelines along with the methane.

Natural gas pipelines have exploded and burned, damaging homes and businesses, at times leaving people injured or dead and overwhelming first responders. The U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) produces a report on "serious" pipeline incidents, those that include a fatality or injury requiring hospitalization. For the 20 years of 1996-2016, PHMSA recorded 858 serious incidents, with 347 fatalities (more than 17 each year) and 1,346 injuries.[126]

In 2012 a natural gas pipeline ruptured and burned in Sissonville, West Virginia. According to the Accident Report of the National Transportation Safety Board,

> *About 20 feet of pipe was separated and ejected from the underground pipeline and landed more than 40 feet from its original location. The escaping high-pressure natural gas ignited immediately. An area of fire damage about 820 feet wide extended nearly 1,100 feet along the pipeline right-of-way. Three houses were destroyed by the fire, and several other houses were damaged. There were no fatalities or serious injuries. About 76 million standard cubic feet of natural gas was released and burned.*[128]

The report stated that "[t]he outside pipe surface was heavily corroded near the midpoint of the rupture" and had suffered "more than 70 percent wall [thickness] loss."

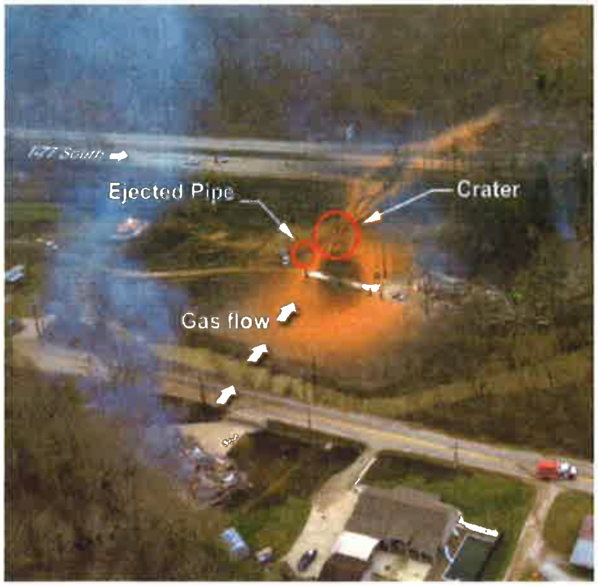
Pipeline corrosion is a factor in some accidents. (See sidebar.) Aging pipes may account for some leaks; however, an analysis of federal data by the nonprofit Pipeline Safety Trust indicated that natural gas transmission lines installed in the 2010's are failing at a higher rate than those installed before 1940. The director of the National Transportation Safety Board's Office of Railroad, Pipeline and Hazardous Materials Investigations stated that "the rapid construction of pipelines in the U.S. is likely a contributing factor."[127]

Natural gas fires are intense and hard for firefighters to control. As such they can pose a danger to nearby vulnerable sites. For example, Spectra Energy's high-pressure Algonquin Incremental Market (AIM) natural gas pipeline will pass only 105 feet from vital structures at the aging Indian Point (NY) nuclear power plant and its 40 years' worth of spent fuel rods. Three New York counties—Rockland County, Westchester and Putnam—have adopted resolutions calling for a comprehensive assessment of the proposed project's potential health and safety impacts;[129, 130, 131] however, construction continues as of the time of this writing.

HEALTH RISKS ASSOCIATED WITH COMPRESSOR STATIONS

Compressors maintain the pressure that keeps gas flowing through the pipelines. Unlike drilling and fracturing activities, compressor stations operate 24 hours a day, year after year. Many are fueled by natural gas, and leak methane and carbon dioxide as they burn the gas. They also leak methane through compressor seals, valves, and connections and through the deliberate venting that is conducted during operations and maintenance. Compressor stations constitute "the primary source of vented methane emissions" in the transmission of natural gas.[132]

People living near compressor stations have experienced a range of symptoms ranging from skin rashes to gastrointestinal, respiratory, neurological and psychological problems.[133, 134] Air samples collected around compressor stations have shown elevated concentrations of many of the dangerous substances associated with fracked gas, including volatile organic compounds, particulate matter and gaseous radon, among others.[135] The federal



Aftermath of a 2012 natural gas explosion and fire.
PHOTO: National Transportation Safety Board.

Agency for Toxic Substances and Disease Registry (ATSDR) found that residents living near a natural gas compressor station in Washington County, PA were exposed to levels of chemicals in the air at which "some sensitive subpopulations (e.g. asthmatics, elderly) may experience harmful effects..."[136] ATSDR noted that the air quality studies conducted at the site "may not have adequately captured uncommon but significant incidents when peak emissions (e.g. unscheduled facility incidents, blowdowns or flaring events) coincide with unfavorable meteorological conditions (e.g. air inversion)."[137]

ATSDR also examined air quality near a natural gas compressor station in another Pennsylvania county, where they found fine particulate matter (PM2.5) at levels where long-term exposure can cause an increase in mortality, respiratory problems, hospitalizations, preterm births, and low birth weight; short-term exposure could harm sensitive populations like those with respiratory problems or heart disease.[138]

HEALTH RISKS ASSOCIATED WITH STORAGE FACILITIES

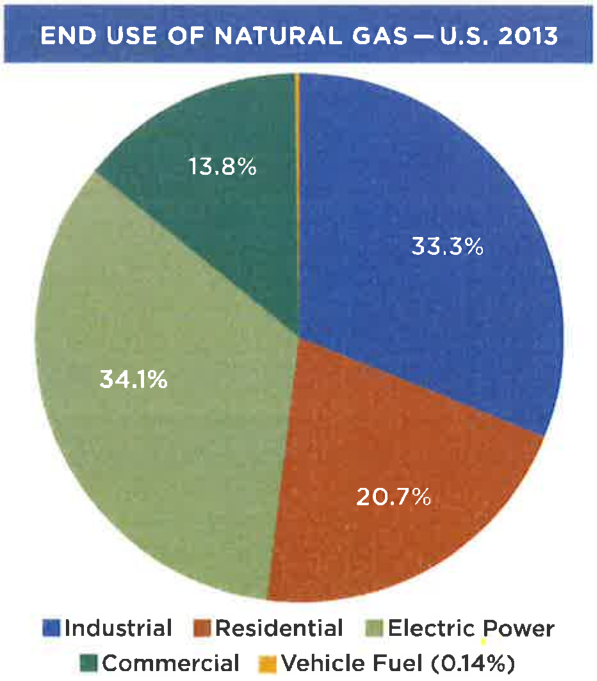
Awareness of potential health effects from natural gas storage facilities was greatly increased by the massive leak at the Aliso Canyon storage facility near Los Angeles, California in 2015-2016. The leak led to the relocation of thousands of families after area residents complained of headaches, nausea and nosebleeds.[139] Health effects from natural gas storage facilities will require further study. Scientists from Stanford and UCLA noted that the intermittent nature of data collection during the Aliso Canyon leak, plus the lack of scientific understanding of the long-term health effects of short-term exposures, left them unsure what to expect from residents' cumulative exposures to chemicals including benzene, hydrogen sulfide, and n-hexane, a neurotoxin.[140] The leak also spread particles of metal including barium, manganese, vanadium, aluminum, and iron in local homes, according to the Los Angeles County Health Department.[141]

Aerial view of the Aliso Canyon gas leak, two months after the [methane leak] incident began. PHOTO: Roy Randall

CLEAN, HEALTHY ALTERNATIVES TO GAS

The decision to reject methane gas as a fuel can appear to be a hard one to make. There are several factors to consider besides the health impacts of energy and climate change. Energy generating capacity, the ability to meet needs such as heating and transportation, and the economic impacts of energy choices, must also be taken into account.

Methane is used for a variety of purposes, including industrial, commercial, and residential. (See chart.) It is also a source of jobs. If the United States does not use methane gas for those purposes, how will we meet those needs?


END USE OF NATURAL GAS—U.S. 2013

Electric power generation, industry, residences and commercial buildings were the major natural gas consuming sectors in the United States during calendar year 2013. Only 0.14 percent went to use as a vehicle fuel. Image by Geology.com using data from the United States Energy Information Administration.

CLEAN ENERGY AND EMPLOYMENT

Employment affects human health in a number of ways.[142] A good-paying, steady job can contribute to good health by making it easier for workers to buy ample and nutritious food, live in a safe and healthy neighborhood, and give their children access to a good education. Jobs are also the source of health insurance for more than half of the civilian workforce. Being unemployed has a direct negative impact on health. Laid-off workers are eighty-three percent more likely to develop a stress-related condition, such as stroke, heart attack, or heart disease; they also have higher levels of depression and anxiety. Thus, the employment capacity of the energy sector is a concern for physicians and other health and public health professionals. At the same time, we must note that not all jobs are created equal, and as the renewable and energy efficiency sectors become cost-competitive nationwide and these sectors expand to create more jobs, we must work with these sectors to ensure they are creating good jobs with family-sustaining wages and benefits. In addition, a just transition will need to ensure that workers who lose their jobs due to the clean-energy transition, such as those who work in the natural gas and coal industries, are provided with transitional support including job training opportunities.

Multiple sources concur that clean energy sources such as solar energy, wind energy and energy efficiency are already providing significant numbers of new jobs in the American economy. However, finding reliable government statistics about clean energy employment is difficult, due to varying definitions of the field, differing research methodologies, and the lack of a single body conducting relevant job surveys. For example, the U.S. Bureau of Labor Statistics does not provide employment statistics for individual industries such as solar and wind. We turn therefore to industry sources to provide job estimates.

OVERALL EMPLOYMENT IN RENEWABLE ENERGY

According to the International Renewable Energy Agency (IRENA), renewable energy employment in the United States increased by six percent in 2015 to reach 769,000 jobs.[143] (IRENA does not include large-scale hydropower in their renewable power estimates; however they do utilize sources which may be renewable but are not clean from a health perspective, such as biomass.) This increase, IRENA noted, was driven by growth in the wind and solar industries.

SOLAR EMPLOYMENT

IRENA calculated solar industry employment in the U.S. to have grown during 2015 by almost 22 percent to reach 209,000 jobs.[144] This accords with the report of the Solar Foundation's *National Solar Jobs Census 2015*, which reported 208,859 U.S. solar workers and an annual growth rate of 20.2 percent.[145] IRENA observed that the U.S. solar industry grew 12 times as fast as overall job creation in the U.S. economy, surpassing employment levels in oil and gas extraction (187,200) and in coal mining (67,929). Most solar jobs are in solar photovoltaics; over half are installation jobs, and almost two thirds occur in the residential market. Given the U.S. Congress' extension of the federal Investment Tax Credit through 2021, continued fast growth of the industry is expected, especially in the utility-scale market, which is however less labor-intensive than the residential sector.

WIND EMPLOYMENT

AWEA, the American Wind Energy Association, reported that the wind industry supported 88,000 jobs at the start of 2016, an increase of 21 percent in a year.[146] They also reported that wind was the nation's leading source of new electricity generating capacity in 2015, outpacing natural gas as well as solar power with a rise in annual installations of 77 percent to reach 8.6 GW. They attributed the large gains in part to the Production Tax Credit (PTC), as wind project developers moved swiftly to complete projects by the end of 2016, the expected end of the PTC qualification period. Job growth in 2015 reflected wind project development and construction, manufacturing sector, and the employment of wind turbine technicians, the fastest-growing profession in the U.S., according to the Bureau of Labor Statistics as cited by AWEA.[147] Texas, Oklahoma, Iowa, Colorado and Kansas were the states with the highest numbers of wind energy employees. Jobs at wind farms, wind-related manufacturing facilities, or both, are now located in 70 percent of U.S. Congressional districts.[148]

ENERGY EFFICIENCY EMPLOYMENT

Energy efficiency jobs occur in five distinct sectors: appliances, including large appliances and lighting efficiency; buildings, including both the green building sector and home and other building retrofitting; public transportation; smart grid and demand management; and vehicles, including electric and hybrid vehicle manufacturing and vehicle fuel efficiency manufacturing projects.[149] While solar and wind energy jobs are perhaps more visible, employment in the energy efficiency sector accounts for roughly four times as many jobs as do solar and wind, according to the American Council for an Energy-Efficient Economy (ACEEE). They estimated there to be 830,000 energy efficiency jobs in the United States as of 2010, and predicted that employment in the sector was increasing at a three percent annual rate, as cited by the Environmental and Energy Study Institute.[150] ACEEE is currently working on a new estimate for U.S. energy efficiency jobs.

COST COMPARISON TO COAL AND GAS INDUSTRIES

Compared to the capital investment required to produce clean energy, it takes a lot more capital to mine fossil fuels, build generating plants and pay on an on-going basis for the fuel. With renewable energies, capital costs occur upfront. Over a longer timeframe, wind and solar are cheaper to produce than coal, and wind is cheaper than natural gas. This is in part because wind and solar (and efficiency) have no fuel costs. In addition, states that don't have their own gas or coal production facilities must spend dollars outside the state to import fuel and are dependent on future pricing. Furthermore, clean energy results in significantly high levels of employment, and the jobs they generate tend to be local, keeping money in the local economy. Currently the coal and gas industries account for more jobs overall, but that is not surprising, given that they produce sixty percent of all the electricity while renewables are producing a mere fraction of that.

CLEAN ENERGY'S GENERATION CAPACITY

The amount of clean energy installed in the United States has been rising and prices have been dropping for renewable energy. In 2015, wind power generated 4.7 percent of total U.S. electricity generation, solar power 0.6 percent, and geothermal 0.4 percent.[151] Is it reasonable to look to these sources to power our nation?

Studies suggest that the answer is yes. While renewable energy (all sources) now account for about 13 percent of electricity generation,[152] an estimate by National Renewable Energy Laboratory estimated that renewable energy sources had in 2012 the potential to supply 482,247 billion kilowatt-hours of electricity annually.[153] Scientists and engineers have already prepared detailed plans to show how we as a nation will be able to meet all our energy needs using clean renewable sources and energy efficiency within 30 to 50 years.[154, 155] One of them, Mark Jacobson, a Stanford University professor of civil and environmental engineering, has developed "roadmaps" that lay out how the 50 U.S. states[156] and 139 nations[157] can transition to 100 percent renewable energy—primarily wind power, water power and sunlight—to meet all their purposes. His U.S. roadmaps envision 80 to 85 percent of existing energy being replaced by these sources by 2030 and 100 percent replaced by 2050. These plans show energy generation sufficient to meet the nation's needs not only for electricity, but also for transportation, heating, cooling, and industry. Some states are already on their way to meeting a substantial fraction of their energy needs from clean renewable energy. Iowa, for example, in 2015 generated 31 percent of its total electric energy generation from wind.[158]

If this can be done, why is it not being done? Several challenges still need to resolved: the intermittency of both solar and wind energy, the upfront capital costs, and management of a more complex electrical grid. At the same time, resolutions to several problems seem to be well on their way.

COSTS: Clean-energy technologies are developing rapidly and are now cheaper than natural gas on a per-kilowatt basis. Concerns over mechanisms to pay the upfront capital costs are being addressed in a variety of ways, such as production tax credits and rebates to homeowners for solar installation. Cost-leveling mechanisms also can work, as is demonstrated by the Regional Greenhouse Gas Initiative (RGGI), under which a cap is placed on the amount of carbon that can be emitted, and the permits to emit carbon are auctioned. This mechanism requires fossil fuels to pay for their carbon emissions, while energy sources that are essentially carbon-free are spared the expense.

POLICY: State policies calling for renewable portfolio standards (RPS) are also effective. This has been demonstrated in Michigan, for example, where the RPS of 10 percent by 2015 was achieved without significant electricity price increases for consumers and with net social benefit, due to reductions in coal burning and a resultant improvement in air quality and health.[159]

RECOMMENDATIONS

To protect human health from the increasing U.S. reliance on methane gas, the best response is twofold. While we still continue to use gas, we must reduce its negative consequences as quickly and effectively as possible: slash leakage, improve or replace leaking infrastructure, and reject practices that allow methane and pollutants to enter the environment.

These steps will help protect human health from the significant levels of water and air pollution and climate forcing we are now experiencing.

At the same time, we must step up the pace of our transition off methane gas, as well as coal and other fossil fuels, and onto renewable energy and energy efficiency. We present here several recommendations that are essential to health and to safeguarding a livable climate.

1. **Measure the global warming impacts of natural gas in the timeframe most likely to prevent irreversible changes.**
    a. The Environmental Protection Agency, Bureau of Land Management and Department of Energy must use the 20-year framework for calculating the global warming potential of methane in the atmosphere, in order to accurately reflect methane's potency in accelerating climate change. Methane over its first 20 years in the atmosphere is 86 times more potent than carbon dioxide.
    b. Methane leakage must be accurately measured on a regular basis across the entire natural gas production process, including extraction, processing, transport, storage and distribution.
    c. Calculate methane leakage at 10 percent, if not more, to reflect recent studies of leakage over the full methane gas life-cycle. This more-encompassing leakage rate makes it apparent that natural gas is as bad for the climate as coal, despite its lower production of carbon dioxide and sulfur dioxide at the point of combustion.

A researcher monitors air emissions near a Marcellus Shale gas well in Pennsylvania. PHOTO: Reid Frazier / The Allegheny Front

2. **Require federal, state and local governments to protect human health from gas-related operations.**
    a. Government plays an important role in protecting human health, and methane gas operations as currently conducted are harming human health. Federal, state and local governments should prioritize the protection of human health in their decisions concerning gas-related projects. Protection of health from the negative impacts of methane gas extraction should be a guiding principle in the relevant decision-making of federal decision-makers including the Environmental Protection Agency (EPA), Federal Energy Regulatory Commission (FERC), and

the Department of the Interior's Bureau of Land Management, as well as state, county and local governments.

b. State and local governments should use all the means at their disposal to protect human health from methane-related operations. State and local governments' right to establish laws and regulations to protect their citizens must be recognized and respected. Assure that state and local governments have the right to establish standards of health protection more stringent than those enacted by the federal government.

c. Ensure that all gas projects must comply with our bedrock environmental laws, including the Clean Water Act, Clean Air Act, Safe Drinking Water Act and the Resource Conservation and Recovery Act.

d. Require companies conducting hydraulic fracturing to fully and transparently declare the chemicals they use in those processes.

e. Oblige state or local governments to require an independent Health Impact Assessment (HIA) before making permitting decisions for a natural gas project. Every HIA should examine projected climate impacts, toxicity, radioactivity impacts, and social impacts.

3. Transition off of fossil fuels and promote the adoption of healthy, low-carbon energy sources.

a. Prioritize the development, adoption and use of low-carbon, low-polluting forms of energy. Promote clean energy technologies that are cost-effective and ready for immediate use, including wind, concentrated solar, roof-top solar, geothermal and heat pumps. Adopt more robust renewable portfolio standards.

b. Prioritize greater application of energy efficiency technologies in all sectors, including appliances, lighting, buildings, transportation and vehicles.

c. Support research and development where they are needed, especially energy storage technologies and construction of a "smart grid" that utilizes and moves energy efficiently.

d. Advocate for solar panel owners' right to send the energy they generate back to the electric company, and be credited for it, without facing charges or penalties ("net metering").

e. As we make the transition to clean energy, assure that the new jobs created in the U.S. economy are good, family-supporting jobs that provide competitive salaries and benefits, and that workers displaced from the fossil fuel industries are provided with job training.

These and similar steps will open the way to a healthy energy future, resulting in cleaner air and water, protecting us all from worsening climate change, strengthening the U.S. economy and creating hundreds of thousands of jobs. Our health and wellbeing, and ultimately our survival, depend on it.

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Flaring from Unconventional Oil and Gas Development and Birth Outcomes in the Eagle Ford Shale in South Texas

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BACKGROUND: Prior studies suggest exposure to oil and gas development (OGD) adversely affects birth outcomes, but no studies have examined flaring—the open combustion of natural gas—from OGD.

OBJECTIVES: We investigated whether residential proximity to flaring from OGD was associated with shorter gestation and reduced fetal growth in the Eagle Ford Shale of south Texas.

METHODS: We conducted a retrospective cohort study using administrative birth records from 2012 to 2015 ($N = 23{,}487$) and satellite observations of flaring activity during pregnancy within 5 km of maternal residence. Multivariate logistic and linear regression models were used to estimate associations between four outcomes (preterm birth, small-for-gestational age, continuous gestational age, and term birthweight) and exposure to a low (1–9) or high (≥ 10) number of nightly flare events, as compared with no exposure, while controlling for known maternal risk factors. We also examined associations with the number of oil and gas wells within 5 km using data from DrillingInfo (now Enverus).

RESULTS: Exposure to a high number of nightly flare events was associated with a 50% higher odds of preterm birth [odds ratio (OR) = 1.50 (95% CI: 1.23, 1.83)] and shorter gestation [mean difference = − 1.9 (95% CI: −2.8, −0.9) d] compared with no exposure. Effect estimates were slightly reduced after adjustment for the number of wells within 5 km. In stratified models these associations were present only among Hispanic women. Flaring and fetal growth outcomes were not significantly associated. Women exposed to a high number of wells (fourth quartile, ≥ 27) vs. no wells within 5 km had a higher odds of preterm birth [OR = 1.31 (95% CI: 1.14, 1.49)], shorter gestation [−1.3 (95% CI: −1.9, −0.8) d], and lower average birthweight [−19.4 (95% CI: −36.7, −2.0) g].

DISCUSSION: Our study suggests exposure to flaring from OGD is associated with an increased risk of preterm birth. Our findings need to be confirmed in other populations. https://doi.org/10.1289/EHP6394

Introduction

Domestic oil production in the United States has nearly doubled in the last decade, whereas natural gas production has risen roughly 50% to an all-time historical high (EIA 2019c, 2019b). Unconventional techniques of directional drilling and hydraulic fracturing (fracking) have allowed for the exploration and extraction of oil and gas from areas that were previously inaccessible or uneconomic and, in many regions, brought oil and gas development (OGD) into closer proximity to homes. More than 17 million people currently live within 1 mi of an oil or gas well in the United States, increasing the potential for exposure to contaminants associated with fossil fuel extraction (Czolowski et al. 2017). The potential health hazards associated with OGD activity include contamination of air (Adgate et al. 2014; Shonkoff et al. 2014; Werner et al. 2015) and water (Jackson et al. 2013) by hazardous chemicals and increased psychosocial stress as a result of noise, increased seismic activity, and social hazards associated with disruptions to the local social fabric (Allshouse et al. 2019; Richburg and Slagley 2019; Witter et al. 2013; Adgate et al. 2014). Fracking involves the injection of fluids, sands, and chemical additives into wells to reduce friction, decrease drill time, or stimulate production and include chemicals that are known carcinogens, mutagens, reproductive and developmental toxins, or endocrine disruptors (Webb et al. 2014; Kassotis et al. 2016; Yost et al. 2016; Stringfellow et al. 2017). These compounds can enter the nearby environment through spills, leaks, and volatilization and the disposal of wastewater.

Several recent studies have suggested that living near OGD during pregnancy may elevate the risk of adverse birth outcomes, including preterm birth (Casey et al. 2016; Whitworth et al. 2018), small-for-gestational age (SGA) birth (Stacy et al. 2015; Tran et al. 2020), low birth weight (Hill 2018; Tran et al. 2020), and neural tube defects (Janitz et al. 2019; Mckenzie et al. 2014). However, the findings have not been consistent across studies: McKenzie et al. (2014), Stacy et al. (2015), and Tran et al. (2020) found no association with preterm birth, and Casey et al. (2016) and Whitworth et al. (2018) found no association with SGA. Fetuses are considered to be highly vulnerable to a variety of toxicants because of their physiologic immaturity and developmental susceptibility (Perera et al. 1999). Preterm birth—which is a major predictor of perinatal mortality and may lead to long-term health problems—remains a major public health concern in the United States, where nearly 400,000 babies are born prematurely each year (Martin et al. 2019). Birthweight is also a significant predictor of later cognitive function and cardiovascular disease, even for infants within the normal weight range born at term (Barker 2006; Shenkin et al. 2004).

The exact exposures through which OGD may elevate the risk of adverse birth outcomes remain unclear. One pathway of exposure that has not yet been examined is flaring. Flaring in this context refers to the intentional, controlled combustion of natural gas during the exploration, production, and processing of natural gas, liquids, and oil. Flaring is used for several days or weeks during well production testing after an oil or gas well is initially drilled and hydraulically fractured. Flaring is also used while performing well maintenance and equipment repairs and as a safety measure at processing plants when equipment becomes overpressurized. In addition, flaring is commonly
natural gas that is dissolved in the oil reco

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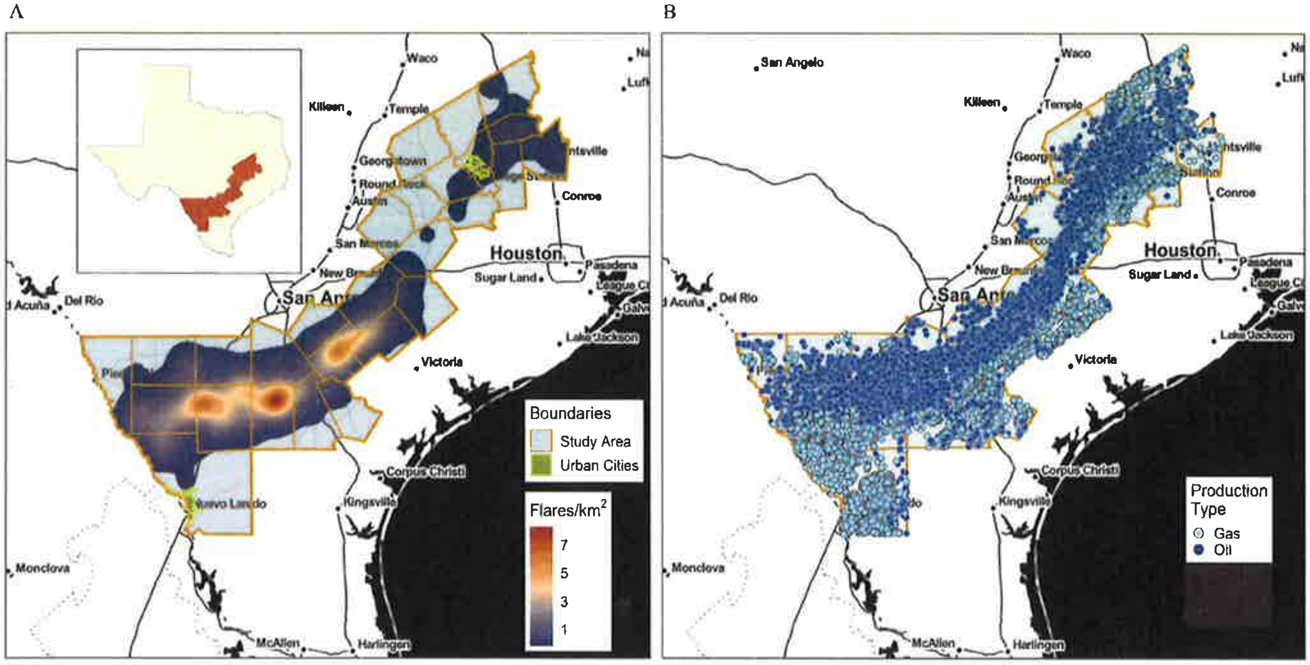

Figure 1. Density of (A) nightly flare events and (B) oil and gas wells across the 27-county Eagle Ford study area, excluding urban areas. Data sources: VIIRS Nightfire (https://www.ngdc.noaa.gov/eog/viirs/) and DrillingInfo (2018) (now Enverus). Counties are delineated in yellow. Green boundaries delineate cities with more than 75,000 people, which were excluded from the analysis. Note: VIIRS, Visible Infrared Imaging Radiometer Suite.

the United States, hydraulic fracturing has enabled the development of previously inaccessible oil shale formations, resulting in the rapid construction of many widely dispersed oil wells in places that lack a pipeline and other infrastructure to economically collect the associated gas. When local opportunities to use the natural gas are also lacking—for example, for reinjection to enhance oil recovery or for electricity generation on site—it is either vented directly to the atmosphere or combusted in routine flaring that can operate continuously for days or months. Global estimates indicate that more than 139 billion m^3 of gas are flared annually, or about 4.6% of the world's natural gas consumption (Elvidge et al. 2009). The United States has the largest number of flare sites globally, burning an estimated 6.5 billion m^3 of natural gas in 2012 (Elvidge et al. 2016). However, regulation and data on the location and timing of flaring is minimal. Monitoring studies indicate that incomplete combustion during the flaring process releases a variety of volatile organic compounds and polycyclic aromatic hydrocarbons along with carbon monoxide, nitrogen oxides, heavy metals, and black carbon (Ite and Ibok 2013; Kindzierski 2000; Leahey et al. 2001; Prenni et al. 2016; Strosher 1996, 2000). Although there have been no studies specifically examining health effects associated with flaring, several of these combustion-related pollutants have been associated with a higher risk of preterm and reduced birthweight in other contexts (Ballester et al. 2010; Brauer et al. 2008; Dadvand et al. 2013). Because flaring is very visible and audible and may produce odors, the practice may also impact fetal growth and development by adding to the anxiety of nearby residents or interrupting sleep (Hiller 2016).

In this study, we utilized satellite observations to characterize exposure to flaring in the Eagle Ford Shale play of south Texas among pregnant women giving birth between 2012 and 2015. The Eagle Ford Shale, which encompasses 27 counties in Southern and Eastern Texas, is one of the most productive oil and gas regions in the country and has experienced a recent boom in production (Figure 1). Due to a weakening of state regulations that previously banned flaring (Willyard 2019), a lack of pipeline capacity for transporting the volumes of natural gas being produced, as well as low gas prices, flaring is a routine practice here. According to the U.S. Energy Information Administration (EIA), Texas flares more natural gas than any other U.S. state (EIA 2019a). Our prior work identified over 43,000 nightly flare events in the region between 2012 and 2016, with a peak in flaring in 2014 and an estimated 4.5 billion m^3 of gas flared over the 5-y period (Franklin et al. 2019). Given the high frequency of flaring in the Eagle Ford Shale, we sought to characterize the effects of prenatal exposure to flaring on the risk of multiple adverse birth outcomes among pregnant women as a possible additional mechanism through which OGD may negatively impact the health of nearby communities.

Methods

Study Population

Study protocols were approved by the institutional review boards of the University of Southern California (#HS-17-00652) and the Texas Department of State Health Service (#14-044). Geocoded administrative birth records were obtained from the Texas Department of State Health Services for the years 2012–2015. Our study population consisted of all singleton births lacking birth anomalies and born to women residing within rural areas of the 27 counties comprising the Texas Eagle Ford Shale play (Texas Railroad Commission 2019) between 19 July 2012 and 31 December 2015 (Figure 1). Women residing in cities with a population of more than 75,000 people were excluded because their exposure to other background sources of air pollutants likely differ from women residing in rural areas. This resulted in the exclusion of residents within the municipal boundaries of Laredo, College Station, and Bryan, Texas. The study start date was chosen because the satellite data used to characterize exposure to flaring became available only beginning 1 March 2012. As such, 19 July 2012 was the first possible birth date of an infant born at $\geq$20 completed weeks (the shortest gestational age in our sample) and, hence, the earliest birth date for which we could assign complete prenatal exposure. The assembly of our study population is illustrated in Figure S1. Gestational age in days was calculated by taking the difference between recorded last menstrual period (LMP) and date of birth. Records missing the year of LMP, month of LMP, or both, were excluded (3.2% of observations); records missing only the day of LMP were recoded using the 15th of the month (2.3% of observations). We excluded a further 1% of births if their gestational age exceeded 44 completed weeks, they were missing gestational age or birthweight, or if they had an improbable combination of sex-specific birthweight for gestational age, following Alexander et al. (1996). Finally, we excluded 13.9% additional observations by restricting our population to women with an LMP between 1 March 2012 and 20 February 2015 to control for truncation or fixed cohort bias (Strand et al. 2011; Wolf and Armstrong 2012). This restriction ensured that all women pregnant during the study period were included in the analysis and resulted in a final sample of $N = 23{,}487$ births. Controlling for truncation bias by restricting on LMP rather than date of birth is particularly important when the start and end day of the study period are not consecutive dates (e.g., 1 January and 31 December), as is the case in our study, and when the exposure of interest is seasonal (as was the case with flaring during our study period, which exhibited some seasonality and peaked in winter).

Oil and Gas Wells

The locations of oil and gas wells were obtained from DrillingInfo (2018) (now Enverus). Our analysis included any permitted well location that had an active lease between 1990 and 2016, excluding inactive wells with a plug date or last reported production date before 1 March 2012. We calculated the number of oil or gas wells within a 5-km radius of the maternal residence as recorded in the birth record and geocoded by the Texas Department of State Health Services. The number of wells within 5 km was then categorized as none, low (1–8), medium (9–26), or high (27–954); these cutoffs corresponded roughly to quartiles of exposure.

Flares

The Nightfire algorithm developed by the National Oceanic and Atmospheric Administration (https://www.ngdc.noaa.gov/eog/viirs/) Earth Observation Group (https://payneinstitute.mines.edu/eog/) detects subpixel (<750-m) combustion sources at night based on multispectral observations obtained from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar Partnership satellite (SNPP) (Elvidge et al. 2013). To characterize OGD-related flaring from these data we included only high-temperature observations of >1,600 K, removing lower temperature observations that are more typical of other industrial and biomass burning sources (Elvidge et al. 2016). Furthermore, we applied a hierarchical density-based spatial clustering method to differentiate flares—which tend to persist for many nights, sometimes for months—from aberrant observations, which we excluded. Details on the clustering method used to filter out aberrant observations are provided elsewhere (Franklin et al. 2019).

In the main analysis, exposure to flaring was estimated for all women residing within 5 km of an oil or gas well and was defined as the number of individual nightly flare events occurring during pregnancy within a 5-km radius of the maternal residence. Exposure to flaring was further categorized into two exposure levels based on the median of exposure among the exposed: low (1–9 flares) or high (10–562 flares). More fine-grained categorization of exposure was not possible due to the low prevalence of exposure in our population (<8%) which would have resulted in a small numbers of cases in each category of exposure and zero cells when including covariates. We also considered the total flared area (in meters squared) from all flares occurring during pregnancy within 5 km of the maternal residence and categorized this variable similarly based on the median of exposure among the exposed: low (1–$24.0\,\mathrm{m}^2$) vs. high (24.2–$1{,}563.6\,\mathrm{m}^2$). We considered flared area because it may be a better proxy for the volume of gas flared and, hence, the quantity of air pollutant emissions. Unlike the estimates we previously derived for flared gas volume (Franklin et al. 2019)—which were derived in aggregate for the study region and rely upon field-level, monthly self-reported administrative data from the State of Texas—flared area is available for individual nightly flare observations directly from VIIRS. Using flared area thus avoids some of the uncertainty in our flared gas volume estimates at the individual flare level and also allows our method to be more easily reproduced in other areas where data on flared gas volume may not be available. Third, we considered the inverse squared distance-weighted sum of flares within 5 km, similarly categorized based on the median of exposure among the exposed: low (4.0×10^{-8} to $1.0\times10^{-6}\,\mathrm{flares/m^2}$) vs. high ($1.0\times10^{-6}$ to $1.0\times10^{-3}\,\mathrm{flares/m^2}$). The inverse squared distance-weighted sum was calculated as follows:

$$\sum_{i=1}^{n}\frac{1}{d_i^2},$$

where i indexes each nightly flare observation within 5 km, d is the distance between each nightly flare and the maternal residence in meters, and n is the total number of nightly flares within 5 km.

Finally, we calculated trimester-specific estimates using our main exposure variable of the number of flares within 5 km. However, because trimester-specific and pregnancy-long exposure estimates were highly correlated (Spearman correlation coefficients of 0.73–0.79; see Figure S2), we did not conduct further analysis of trimester-specific exposures.

Outcome Measures

We investigated four outcomes: preterm birth (<37 completed weeks of gestation), SGA, continuous gestational age in days, and birthweight among term births (tBW; $\geq$37 completed weeks of gestation). SGA was defined as birthweight below the sex-specific 10th percentile of birthweight by gestational week based on the smoothed percentiles for U.S. singleton live births during 2009–2010 (Talge et al. 2014). SGA status was not determined for births at <22 weeks of gestation because the distributions provided in Talge et al. (2014) included only gestational ages between 22 and 44 weeks.

Statistical Analysis

We used separate multivariate linear or logistic regression models to estimate the association between flares and our four outcomes while adjusting for the following known risk factors: maternal age (in 5-y increments from <20 to $\geq$35 y), race/ethnicity (Hispanic, non-Hispanic white, other), nativity (U.S. or foreign born), educational attainment (<high school, high school or equivalent, >high school), prepregnancy body mass index [BMI; underweight or normal ($\leq 25\,\mathrm{kg/m^2}$), overweight (≥ 25–$30\,\mathrm{kg/m^2}$), or obese ($\geq 30\,\mathrm{kg/m^2}$)], smoking (ever/never during pregnancy), insurance based on primary source of expected payment (private vs. Medicaid, self-pay, or other), parity (nulliparous vs. multiparous), high-risk pregnancy (any of the following: prepregnancy or gestational hypertension or diabetes, preeclampsia, or eclampsia), sex of infant, adequacy of prenatal care (no care, inadequate, intermediate, adequate, >adequate), year of birth (to control for secular trends), and season of birth. Models of tBW were additionally adjusted for gestational age (in weeks). Maternal BMI was calculated from recorded maternal height and weight. Because the prevalence of underweight was very low in our population (3.2%), the categories of underweight and normal BMI were collapsed. Prenatal care was characterized using the Kotelchuck or Adequacy of Prenatal Care Utilization Index, which combines the initiation of prenatal care and the number of prenatal visits to derive a ratio of observed to expected visits, with the number of expected visits based on the American College of Obstetricians and Gynecologists prenatal care standards for uncomplicated pregnancies and adjusted for the gestational age when care began and for the gestational age at delivery (Kotelchuck 1994). Women with expected primary sources of payment of self-pay or other were categorized with the publicly insured due to their low counts and because they more closely resembled those with public insurance than they did women with private insurance with respect to education, nativity, race/ethnicity, and prenatal care. Of the 23,487 births in our sample population, 23,158 included nonmissing information for all covariates and constituted the sample for the multivariate regression analyses.

Because proximity to wells has been associated with adverse birth outcomes in prior studies, and flaring does not occur at all well sites, we conducted a secondary analysis in which we included the number of wells within 5 km as an additional covariate in our models. Because prior studies suggest that women of color may be more vulnerable to air pollutant exposures (Ito and Thurston 1996; Morello-Frosch et al. 2010), we conducted a stratified analysis to examine the effects of flaring among Hispanic women and non-Hispanic white women. There were too few women of other races or ethnicities to enable additional stratification. In a post hoc analysis, we also included an indicator variable for residence in a census-designated place (in our study area, a small town or settlement, as opposed to a more rural setting) to see if rurality confounded the association between flaring and the outcomes. All statistical modeling was conducted using Stata IC (release 15.1; StataCorp).

Results

The final sample population included 23,487 births, 10.6% of which were preterm. The majority (55%) of women in the study population identified as Latina or Hispanic, 37% as non-Hispanic white, with few women identifying as non-Hispanic black (6.5%) or Asian or Pacific Islander (0.66%). Nearly 60% of women were on public health insurance (Medicaid) and 17% were foreign born. Other characteristics of the sample population are given in Table 1.

Most women (92%) were not exposed to flares within 5 km of their residence during pregnancy, whereas 74% were exposed to at least one oil or gas well within 5 km. Women who were exposed to flaring were slightly younger, less likely to be African American, less likely to be foreign born, and received lower levels of prenatal care than women who were not exposed to flaring (Table 1). The unadjusted preterm birth rate, mean gestational age, and tBW varied between women exposed to flaring and those who were not ($p < 0.0005$, $p = 0.02$ and $p = 0.06$, respectively, Pearson's chi-square or F-test), with women exposed to high levels of flaring having a higher preterm birth rate and lower mean gestational age and tBW compared with those who were not exposed (Table 2). Similar patterns were observed with respect to residential proximity to oil and gas wells (higher preterm birth rate, $p = 0.04$; shorter gestational age, $p = 0.0005$; and lower tBW, $p = 0.007$ compared with the unexposed). As expected, our outcomes also varied by the risk factors we identified *a priori*, including maternal age, education, race/ethnicity, prenatal care, smoking, insurance, high-risk pregnancy status, and parity (see Table S1).

In multivariate models, exposure to a high level of flaring was associated with a 50% higher odds of preterm birth {odds ratio (OR) = 1.50 [95% confidence interval (CI): 1.23, 1.83]} and shorter gestation [mean difference of −1.9 (95% CI: −2.8, −0.9) d] compared with no exposure (Figure 2A,C). Adjusting for the number of wells within 5 km reduced the effect estimates slightly [OR for preterm birth = 1.41 (95% CI: 1.11, 1.69); mean difference of −1.5 (95% CI: −2.4, −0.5) d] and also suggested that exposure to low levels of flaring (1–9 flares) was associated with a reduced odds of preterm birth [OR = 0.76 (95% CI: 0.60, 0.97)] (Figure 2A,C). Associations between flaring and fetal growth outcomes (SGA and tBW) were not statistically significant at $p < 0.05$ (Figure 2B,D). In models that included both the number of flares and wells within 5 km, the number of wells was a significant predictor of a higher odds of preterm birth [OR = 1.31 (95% CI: 1.14, 1.49) comparing the highest quartile vs. no exposure], shorter gestational age [mean difference of −1.3 (95% CI: −1.9, −0.8) d comparing the highest quartile vs. no exposure], as well as reduced tBW [mean difference of −19.4 (95% CI: −36.7, −2.0) g comparing the highest quartile vs. no exposure and controlling for gestational age] (see Tables S2 and S3). All other covariates generally had effect estimates in the expected direction.

When we modeled exposure to flaring as flared area within 5 km, rather than counts, results were generally consistent: Exposure to a high-flared area was associated with a 47% increased odds of preterm birth [OR = 1.47 (95% CI: 1.20, 1.79)] and a reduction in mean gestational age [−2.0 (95% CI: −3.0, −1.1) d] compared with the unexposed in models that did not adjust for the number of wells within 5 km (see Tables S4 and S5). Including the number of wells in the models again reduced these effects estimates slightly [OR for preterm birth = 1.34 (95% CI: 1.08, 1.65); mean difference of −1.7 (95% CI: −2.6, −0.7) d] (see Tables S4 and S5). Associations between exposure to a high-flared area and SGA or tBW were not statistically significant. Exposure to a low-flared area was associated with a reduced odds of preterm birth, but the association was not statistically significant at $p < 0.05$ in models with or without adjustment for the number of wells within 5 km. The number of wells remained a significant predictor of higher odds of preterm birth [OR = 1.31 (95% CI: 1.14, 1.49) comparing the highest quartile vs. no exposure], shorter gestational age [mean difference of −1.3 (95% CI: −1.9, −0.8) d comparing the highest quartile vs. no exposure], and reduced tBW [mean difference of −19.5 (95% CI: −36.8, −2.2) g comparing the highest quartile vs. no exposure and controlling for gestational age] in models of flared area. Multivariate models using our third exposure metric of inverse squared distance-weighted sum of flares within 5 km also resulted in very similar effect estimates for the associations between high exposure to flares and our four outcomes (see Tables S6 and S7).

Stratified models using our primary exposure metric suggested that the association between the number of flares within 5 km and preterm birth was present only among Hispanic women. Among Hispanics, exposure to a high level of flaring was associated with a 61% higher odds of preterm birth [OR = 1.61 (95% CI: 1.25, 2.08)] and shorter gestation [mean difference = −2.2 (95% CI: −3.4, −0.9) d] in models that controlled for the number of wells within 5 km (Figure 3A,C; see also Tables S8 and S9). Among non-Hispanic white women, the corresponding OR for preterm birth = 0.78 (95% CI: 0.50, 1.20); the corresponding mean differences in gestational age = 0.0 (95% CI: −1.5, 1.5) d (Figure 3A,C; see also Tables S8 and S9). Associations between flaring and SGA or tBW were not statistically significant in stratified models of Hispanic or non-Hispanic white women (Figure 3B,D).

Table 1. Characteristics of the study population by degree of flaring within 5 km of the maternal residence, Eagle Ford Shale, Texas, births between 19 July 2012 and 31 December 2015 ($N = 23{,}487$).

Variable	All ($N = 23{,}487$)	No flaring ($n = 21{,}635$)	Low flaring ($n = 921$)	High flaring ($n = 931$)	*p*-Value[a]
Age [y (mean ± SD)]	26.4 ± 5.8	26.4 ± 5.8	26.2 ± 5.7	25.9 ± 5.6	0.032
Education [*n* (%)]					0.15
<High school	5,318 (23)	4,907 (23)	203 (22)	208 (22)	
High school diploma/GED	7,776 (33)	7,127 (33)	306 (33)	343 (37)	
Some college or more	10,375 (44)	9,583 (44)	412 (45)	380 (41)	
Missing	18 (0.1)	18 (0.1)	—	—	
Race/ethnicity [*n* (%)]					<0.0005
Hispanic	12,904 (55)	11,853 (55)	488 (53)	563 (60)	
Non-Hispanic white	8,704 (37)	7,992 (37)	388 (42)	324 (35)	
Non-Hispanic black	1,535 (6.5)	1,470 (6.8)	36 (3.9)	29 (3.1)	
Non-Hispanic Asian/Pacific Islander	156 (0.7)	143 (0.7)	<10	<10	
Other, including mixed race	160 (0.7)	153 (0.7)	<10	<10	
Missing	28 (0.1)	24 (0.1)	—	<10	
Foreign born [*n* (%)]					<0.0005
No	19,539 (83)	17,861 (83)	822 (89)	856 (92)	
Yes	3,941 (17)	3,768 (17)	98 (11)	75 (8.1)	
Missing	<10	<10	<10	—	
BMI {kg/m^2 [*n* (%)]}					0.33
Underweight/normal	10,026 (43)	9,227 (43)	416 (45)	383 (41)	
Overweight	6,185 (26)	5,689 (26)	227 (25)	269 (29)	
Obese	7,106 (30)	6,559 (30)	270 (29)	277 (30)	
Missing	170 (0.7)	160 (0.7)	<10	<10	
Prenatal care [*n* (%)]					<0.0005
None	1,858 (7.9)	1,708 (7.9)	62 (6.7)	88 (9.5)	
Inadequate	4,227 (18)	3,834 (18)	190 (21)	203 (22)	
Intermediate	1,994 (8.5)	1,807 (8.4)	87 (9.5)	100 (11)	
Adequate	7,531 (32)	6,951 (32)	291 (32)	289 (31)	
>Adequate	7,877 (34)	7,335 (34)	291 (32)	251 (27)	
Smoking during pregnancy [*n* (%)]					0.69
No	22,226 (95)	20,479 (95)	867 (94)	880 (95)	
Yes	1,183 (5.0)	1,082 (5.0)	51 (5.5)	50 (5.4)	
Missing	78 (0.3)	74 (0.3)	<10	<10	
Insurance [*n* (%)]					0.02
Public	13,808 (59)	12,695 (59)	566 (61)	547 (59)	
Private	7,690 (33)	7,068 (33)	296 (32)	326 (35)	
Self-pay	963 (4.1)	910 (4.2)	23 (2.5)	30 (3.2)	
Other	994 (4.2)	931 (4.3)	36 (3.9)	27 (2.9)	
Missing	32 (0.1)	31 (0.1)	—	<10	
High-risk pregnancy [*n* (%)]	2,240 (10)	2,045 (9.5)	99 (11)	96 (10)	0.32
Parity					0.56
Nulliparous	8,243 (35)	7,611 (35)	320 (35)	312 (34)	
Multiparous	15,237 (65)	14,017 (65)	601 (65)	619 (65)	
Missing	<10	<10	—	—	
Year of birth [*n* (%)]					<0.0005
2012	698 (3.0)	655 (3.0)	14 (1.5)	29 (3.1)	
2013	7,471 (32)	6,765 (31)	444 (48)	262 (28)	
2014	8,088 (34)	7,474 (35)	316 (34)	298 (32)	
2015	7,230 (31)	6,741 (31)	147 (16)	342 (37)	
Season of birth [*n* (%)]					0.38
Spring (MAM)	5,443 (23)	5,002 (23)	218 (24)	223 (24)	
Summer (JJA)	6,229 (27)	5,727 (26)	268 (29)	234 (25)	
Fall (SON)	5,974 (25)	5,505 (25)	218 (24)	251 (27)	
Winter (DJF)	5,841 (25)	5,401 (25)	217 (24)	223 (24)	
Residence in census-designated place [*n* (%)]	11,883 (51)	10,809 (50)	475 (52)	599 (64)	<0.0005

Note: Cells with counts <10 have been suppressed. Percents may not sum to 100 due to rounding. Exposure to flaring was defined based on the median number of flares within 5 km during pregnancy among the exposed (low: 1–9, high: ≥10). —, No data; BMI, body mass index; DJF, December, January, February; GED, general education development; JJA, June, July, August; MAM, March, April, May; SD, standard deviation; SON, September, October, November.

[a] Pearson's chi-square test or *F*-test by level of flaring exposure.

Our post hoc sensitivity analysis including residence in a census-designated place in the main preterm birth model did not change the magnitude, direction, or statistical significance of effect estimates. The coefficients for census-designated place was also not statistically significant (see Table S10).

Discussion

As far as we are aware, this is the first study to examine the potential effects of flaring from oil and gas extraction on human health. Our retrospective cohort study of births between 2012 and 2015 in the Eagle Ford Shale region of south Texas suggests that prenatal exposure to flaring from OGD is associated with a significant increase in the risk of preterm birth and a shorter length of gestation among pregnant women living nearby. Because we included the number of oil and gas wells in our models, our findings suggest the effects of flaring on the length of gestation are independent of other potential exposures related to oil and gas wells.

Our stratified analysis suggested that Hispanic women were vulnerable to the effects of flaring on preterm birth, whereas non-Hispanic white women were not. As far as we are aware, this is the

Table 2. Birth outcomes by degree of flaring during pregnancy and number of oil and gas wells within 5 km of the maternal residence, Eagle Ford Shale, Texas, 2012–2015 ($N = 23{,}487$).

	Flares within 5 km				Wells within 5 km				
	0 ($n = 21{,}634$)	Low ($n = 921$)	High ($n = 931$)	p-Value[a]	0 ($n = 6{,}176$)	Low ($n = 6{,}215$)	Medium ($n = 5{,}482$)	High ($n = 5{,}614$)	p-Value[a]
Preterm birth [n (%)]	2,269 (10.5)	81 (8.8)	131 (14.1)	<0.0005	598 (9.7)	656 (10.6)	618 (11.3)	609 (10.9)	0.04
Small for gestational age [n (%)]	2,224 (10.3)	86 (9.3)	94 (10.1)	0.65	635 (10.3)	648 (10.4)	574 (10.5)	547 (9.7)	0.56
Gestational age [weeks (mean ± SD)]	38.5 ± 2.1	38.6 ± 1.9	38.3 ± 2.2	0.02	38.6 ± 2.1	38.5 ± 2.2	38.5 ± 2.2	38.5 ± 2.1	0.0005
Term birthweight [g (mean ± SD)]	3,284 ± 543	3,288 ± 509	3,241 ± 529	0.06	3,301 ± 545	3,282 ± 548	3,268 ± 540	3,276 ± 529	0.007

Note: Exposure to flaring was defined based on the number of nightly flares (low: 1–9, high: 10–562), with the cutoff corresponding to the median of exposure among the exposed. The number of wells was categorized as zero, low (1–8), medium (9–26), or high (27–524), with cutoffs corresponding roughly to quartiles of exposure. SD, standard deviation.
[a] Pearson's chi-square test or F-test by level of exposure.

first study to document greater health impacts associated with OGD among women of color. A history of government-sanctioned discrimination in housing, employment, and education have led Hispanics in Texas to be socioeconomically disadvantaged, with a 2014 median household income of $41,177 compared with $65,786 for non-Hispanic whites and with a greater proportion living below the federal poverty level (23% vs. 9.3% among non-Hispanic whites) (Texas Health and Human Services Commission 2014). Reasons why women of color and lower socioeconomic status may experience greater vulnerability to flaring could relate to differences in preexisting health status (because income and education are directly related to health); greater co-exposures to other pollutants (e.g., because pollution sources are disproportionately located in communities of color); a compromised ability to cope with the adverse effects of pollution due to poor nutrition or limited access to health care, preventative or social services; and modifying effects of psychosocial stress associated with living in poverty or experiencing discrimination. Belonging to a racial or ethnic group that experiences systemic discrimination may confer greater vulnerability due to the physiological effects of chronic psychosocial stress (Geronimus 1992). Evidence suggests that chronic stress can result in physiological wear and tear on the body that can increase vulnerability to environmental stressors by impairing immune function, increasing the absorption of toxicants (McEwen 1998), by compromising the body's defense systems, or by directly causing illness or affecting the same physiological process as the environmental toxicant (Clougherty and Kubzansky 2009; Gee and Payne-Sturges 2004; Gordon 2003; Morello-Frosch and Shenassa 2006). Although we were not able to directly examine stress or say why Hispanic women in our study were more vulnerable, our findings are consistent with prior studies that found socially disadvantaged women—including African Americans and residents of socioeconomically disadvantaged neighborhoods—are more vulnerable to the impacts of ambient air pollution, including larger reductions in birth weight associated with exposure to particulate matter (Erickson et al. 2016; Morello-Frosch et al.

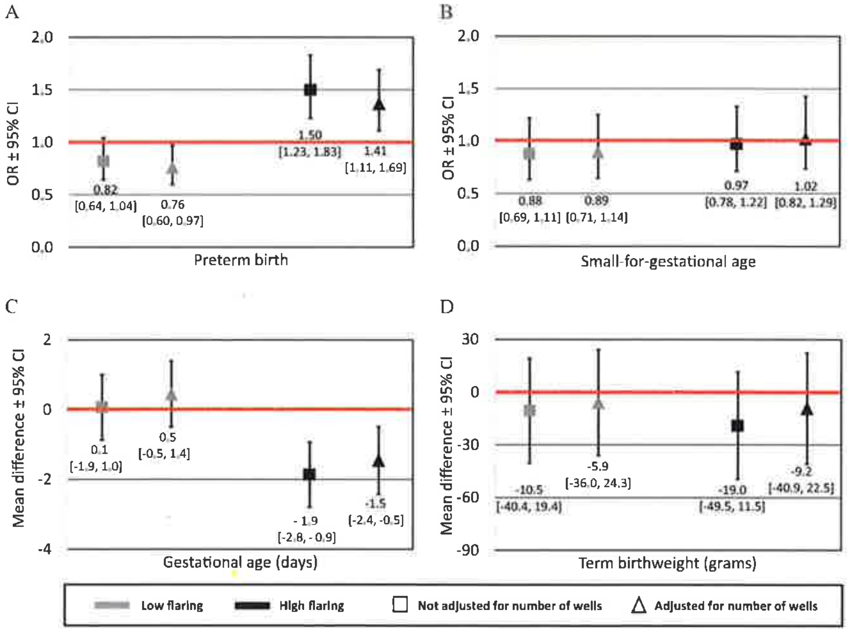

Figure 2. Estimated associations between the number of flares within 5 km of maternal residence and (A) the odds of preterm birth, (B) the odds of small-for-gestational age birth, (C) gestational age, and (D) term birthweight, Eagle Ford Shale, Texas, 2012–2015 ($N = 23{,}158$). Full numeric data for models that are unadjusted (Model 1) and adjusted (Model 2) for the number of oil and gas wells within 5 km are provided in Tables S2 and S3. Figures show effect estimate and 95% CIs comparing infants with prenatal exposure to a low (1–9) and high (10–562) number of nightly flare events within 5 km of the maternal residence to unexposed infants. All estimates are adjusted for maternal age, race/ethnicity, nativity, education, prepregnancy BMI, smoking, insurance, parity, high-risk pregnancy, infant sex, prenatal care, year of birth, and season of birth. Models of term birthweight additionally controlled for gestational age. Red lines indicate the null. Note: BMI, body mass index; CI, confidence interval; OR, odds ratio.

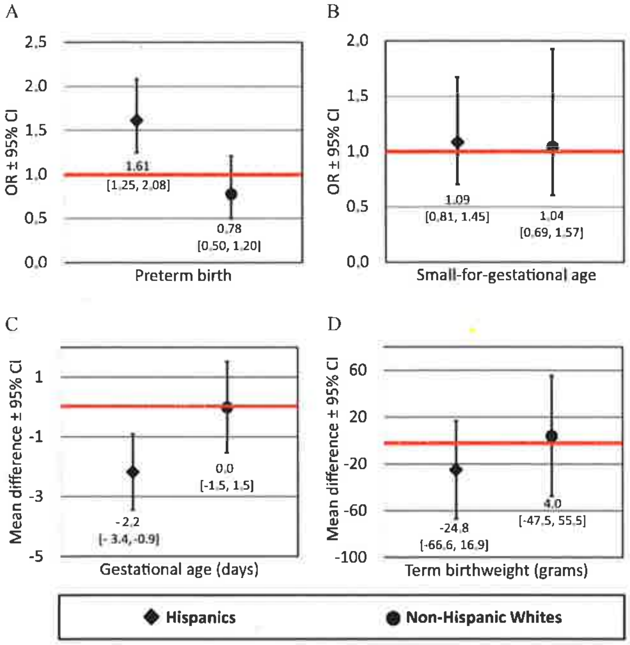

Figure 3. Estimated associations from models stratified by ethnicity between the number of flares within 5 km of maternal residence and (A) the odds of preterm birth, (B) the odds of small-for-gestational age birth, (C) gestational age, and (D) term birthweight, Eagle Ford Shale, Texas, 2012–2015 ($N = 12{,}781$, Hispanic women and $N = 8{,}566$ non-Hispanic white women). Full numeric data are provided in Tables S8 and S9. Figures show effect estimates and 95% CIs comparing infants with prenatal exposure to a low (1–9) and high (10–562) number of nightly flare events within 5 km of the maternal residence to unexposed infants. All estimates are adjusted for the number of oil and gas wells within 5 km, maternal age, nativity, education, prepregnancy BMI, smoking, insurance, parity, high-risk pregnancy, infant sex, prenatal care, year of birth, and season of birth. Models of term birthweight additionally control for gestational age. Red lines indicate the null. Note: BMI, body mass index; CI, confidence interval; OR, odds ratio.

2010; Westergaard et al. 2017). In addition, it is possible there is a threshold effect of flaring and that the lack of an association among non-Hispanic white women that we observed may have been the result of the fact that they were exposed to a lower average number of nightly flare events than Hispanic women (mean of 24.1 vs. 36.3 among the exposed).

We found no evidence of an association between flaring and SGA or reduced birthweight among term infants when controlling for gestational age. The lack of strong associations with these outcomes may be due to a lack of a true effect on fetal growth independent of gestational age or to power limitations resulting from the low prevalence of exposure to flaring in our study population. For example, given the prevalence of SGA (10.2%) and exposure to flaring (7.9%) in our study population, we estimate that we had power of only 0.52 to detect a true OR of 1.2 at $\alpha = 0.05$.

We found that women exposed to low levels of flaring had a reduced odds of preterm birth compared with women with no exposure in models that controlled for well density. This counterintuitive finding was no longer statistically significant when we measured exposure to flaring on the basis of flared area or the inverse squared distance-weighted sum of nightly flare events, which may better approximate the quantity and proximity of flared gas than the number of flares, suggesting the association may have been spurious, or the result of a threshold or nonlinear effect that we were not able to estimate given the small number of exposed women in our sample (<8%). It is also possible that low levels of flaring may appear protective because women exposed to low levels of flaring live in more rural settings than those exposed to no flaring [median (mean) population density = 180 (699) people per square kilometer for the low-flare group vs. 452 (1,063) for the no-flare group] and are, therefore, less exposed to other pollutants such as traffic-related air pollution, resulting in residual confounding. However, a lack of regulatory air pollution monitoring in our study region prohibits us from being able to further assess this potential source of bias. Adding an indicator variable for residence in a census-designated place (in our study area, a small town, as opposed to a more rural setting) to our models in a post hoc analysis did not change the magnitude, direction, or statistical significance of effect estimate for the association between low levels of flaring and preterm birth (see Table S9).

In addition to flaring, we also found that living within 5 km of oil and gas wells was independently associated with adverse birth outcomes, including a higher odds of preterm birth, reduced gestational age, and reduced tBW, controlling for gestational age. The association with preterm birth is consistent with previous studies from Pennsylvania and Northern Texas in areas of OGD but absent of significant flaring activity (Casey et al. 2016; Whitworth et al. 2018). Other studies from Southwest Pennsylvania, Colorado, and California have found no evidence of such an association with preterm birth (Mckenzie et al. 2014; Stacy et al. 2015; Tran et al. 2020). In contrast to our findings, the majority of previous studies have found little evidence of an association between residential proximity to OGD and birthweight, with the exception of Stacy et al. (2015) and Tran et al. (2020). Our contrasting findings could be related to differences in our study design and the nature of OGD in the Eagle Ford Shale, which includes significant oil as well as gas production and conventionally drilled as well as unconventionally drilled wells. (With the exception of the California study, prior studies have focused on natural gas wells that were unconventionally drilled.)

Our findings hold broader implications for other populations exposed to flaring from OGD. Flaring activity has increased dramatically in the United States over the last five years, spiking by nearly 50% in 2018 from the previous year, the largest absolute gains of any country (World Bank 2019). Beyond the Eagle Ford Shale, flaring is common in the Permian Basin of West Texas and Eastern New Mexico as well as the Bakken Shale of North Dakota and Western Montana. In fact, a recent study suggests that as of 2015, the Permian Basin has had more flare activity and appears to flare larger volumes, on average, than the Eagle Ford play (Willyard and Schade 2019). In the Bakken Shale play, it is estimated that 28% of North Dakota's total produced natural gas was flared (Gvakharia et al. 2017). The health impacts of flaring therefore warrant additional study, and our findings require replication in other populations. Prior work has demonstrated associations between flaring and increased risk of stillbirth among cattle as well as increased risk of calf mortality (Bamberger and Oswald 2012). However, we are unaware of any previous studies assessing the health impacts of flaring from OGD among humans.

We utilized a novel exposure metric derived from infrared satellite observations that provides an objective, highly spatially and temporally resolved measure of flaring activity. In places such as our study region, where industrial activity is minimal, combustion sources detected using this method are unlikely to come from sources other than flaring. This approach provides distinct advantages over alternative available measures of flaring, including self-reported regulatory data, which is likely to underestimate the magnitude of flaring and is provided only in the aggregate (monthly, lease-level). However, our measure only indirectly reflects potential exposures, including air pollutant emissions. We are, therefore, unable to determine the mechanism(s) through which flaring may adversely affect birth outcomes. Monitoring studies have indicated that incomplete combustion during the flaring process can release a variety of air pollutants, including particulate matter, which has been linked to preterm birth and reduced fetal growth in other contexts (Ballester et al. 2010; Brauer et al. 2008; Dadvand et al. 2013). However, there is a lack of air pollutant monitoring data in areas with flaring due to OGD, which are primarily rural.

Because we relied on live birth records, we were unable to assess potential effects of flaring on the risk of miscarriage. We were also unable to examine critical windows of exposure due to the high correlation between pregnancy-long and trimester-specific estimates of exposure to flaring in our population. Another limitation of our study is that we were unable to capture maternal mobility because only the birth mother's place of residence at the time of birth is recorded in the birth records. Prior studies have suggested that ignoring residential mobility may bias associations toward the null due to nondifferential exposure misclassification, and that moving distances during pregnancy are typically relatively short and within the same county (Bell and Belanger 2012; Chen et al. 2010; Hodgson et al. 2015; Lupo et al. 2010; Miller et al. 2010; Pennington et al. 2017).

Together, our findings suggest that living within 5 km of OGD wells and flaring activity may have had a significant adverse effect on birth outcomes among pregnant women in the Eagle Ford region. The fact that much of the region is low income and approximately 50% of residents living within 5 km of an oil or gas well are people of color raises environmental justice concerns about the potential health impacts of the oil and gas boom in south Texas (Johnston et al. 2016). Measures to minimize flaring—such as more stringent regulation of flaring or investments in renewable energy and energy efficiency measures that reduce reliance on fossil fuels overall—could protect the health of infants.

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Unconventional natural gas development and birth outcomes in Pennsylvania, USA

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Abstract

Background—Unconventional natural gas development has expanded rapidly. In Pennsylvania the number of producing wells increased from zero in 2005 to 3689 in 2013. To our knowledge, no prior publications have focused on unconventional natural gas development and birth outcomes.

Methods—We performed a retrospective cohort study using electronic health record data on 9384 mothers linked to 10946 neonates in the Geisinger Health System from January 2009-January 2013. We estimated cumulative exposure to unconventional natural gas development activity with an inverse-distance squared model that incorporated distance to the mother's home; dates and durations of well pad development, drilling, and hydraulic fracturing; and production volume during the pregnancy. We used multilevel linear and logistic regression models to examine associations between activity index quartile and term birth weight, preterm birth, low 5 minute Apgar score and small size for gestational age, while controlling for potential confounding variables.

Results—In adjusted models, there was an association between unconventional natural gas development activity and preterm birth that increased across quartiles, with a fourth quartile odds ratio of 1.4 (95% CI: 1.0-1.9). There were no associations of activity with Apgar score, small for

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Conflicts of Interest We declare that we have no conflicts of interest.

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gestational age, or term birth weight (after adjustment for year). In a *post-hoc* analysis, there was an association with physician-recorded high-risk pregnancy identified from the problem list (fourth vs. first quartile, 1.3 [95% CI: 1.1-1.7]).

Conclusion—Prenatal residential exposure to unconventional natural gas development activity was associated with two pregnancy outcomes, adding to evidence that unconventional natural gas development may impact health.

INTRODUCTION

The last decade has seen rapid development of unconventional natural gas resources worldwide; the International Energy Agency reports that 18% of global gas production now comes from unconventional sources. The steepest increases have occurred in the United States (U.S.) and in particular in the Marcellus shale in Pennsylvania. From 2006 to 2013, annual conventional gas production in Pennsylvania was stable at around 5.7 billion cubic meters (bcm); prior to 2009, unconventional production was less than 10 bcm, and then production increased rapidly to 3048 bcm in 2013.

Unconventional natural gas development is a large-scale multi-stage process.[1-4] Developers use diesel equipment to clear land for well pads, transport materials, and drill multiple wells per pad. Directional drilling, first vertically and then horizontally, and hydraulic fracturing ("fracking") differentiate this process from conventional development. Hydraulic fracturing involves injecting millions of liters of water mixed with sand and chemicals into the borehole causing fractures in the shale formation. Fracturing fluids, flowback and produced water, and natural gas then flow to the surface for collection and use. Gas is sometimes flared, releasing pollutants. Wells produce natural gas at high rates for the first year, with a rapid decline over the first three years.

Prior studies have demonstrated environmental impacts from the various stages of unconventional natural gas development including pollution of air,[5-9] surface water,[10] groundwater,[11,12] and soil as recently reviewed.[1-3] Truck traffic, drilling, hydraulic fracturing, and production can generate diesel particulate matter, fine particulate matter ($PM_{2.5}$), methane, NO_x, and volatile organic compounds, which are also ozone precursors.[5-7,13] Some of these pollutants, most consistently $PM_{2.5}$, NO_x, SO_x, and ozone, have been associated with adverse birth outcomes including low or reduced birth weight14-16 and preterm birth.14,17,18 $PM_{2.5}$ and ozone are regional air pollutants, so women living long distances from unconventional natural gas development could experience effects.

Expectant mothers could also be exposed to water pollution from unconventional natural gas development. A recent study identified 2-n-butoxyethanol – a chemical found in flowback water from the process, which might be a general indicator of its contamination – in household well water in Pennsylvania.[12] In addition, people living in communities near unconventional natural gas development commonly report symptoms (e.g., upper respiratory symptoms, headaches), and may experience psychosocial stressors from rapid industrial development, increased motor vehicle traffic, potential influences on environmental radon pathways, noise, and infusion of short-term workers.[1,4,19-23] Some of these exposures have

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also been linked to negative birth outcomes.[24,25] A recent study in Colorado reported that density of and proximity to natural gas wells were associated with congenital heart and neural tube defects, but not with birth weight or preterm birth.[26] This study did not distinguish between conventional and unconventional wells, and mainly described associations with conventional wells since the Energy Information Agency estimated that only 25% of natural gas produced in Colorado in 2009 came from unconventional sources. There is an unpublished study that found mothers living near unconventional natural gas development in Pennsylvania gave birth to infants with increased prevalence of low birth weight, low Apgar scores, and small for gestational age.[27]

In this study, we exploited the geographic overlap of the Geisinger Health System and unconventional natural gas development in Pennsylvania to conduct a retrospective cohort study by linking electronic health record data to estimates of exposure to the activities during pregnancy. Despite calls for health studies,[28,29] to our knowledge there is only one published population-based study focused on unconventional natural gas development and objective health outcomes.[30] We evaluated associations between an index of unconventional natural gas development activity and four birth outcomes.

METHODS

Study area and participants

The Geisinger Health System serves a primary market of approximately 40 counties in central and northeast Pennsylvania, a region with a 2010 population of over 4 million residing in over 1200 communities defined as townships, boroughs, and census tracts in cities.[31] Patients with a Geisinger primary care provider are representative of the general population based on age, sex, race/ethnicity, and rural residence.[32] Neonates were delivered at two hospitals, Geisinger Medical Center in Danville, which has a Level IV neonatal intensive care unit (NICU), and Geisinger Wyoming Valley in Wilkes-Barre, which has a Level II NICU. The Institutional Review Board at the Geisinger Health System reviewed and approved the study.

Singleton births to women who delivered at Geisinger between 2006 and January 2013 were eligible for inclusion. We identified births and deliveries using International Classification of Diseases, Ninth Revision codes (i.e., V27.x, V30.x) in mother and neonate electronic health records. We used medical record numbers and other data found in the electronic health record to link mothers with their neonates. We excluded those whom we could not match, stillbirths, and neonates with serious birth defects, birth weights < 500g or gestational ages < 22 weeks. Only mother's 2013 address was available from the electronic health record, so we assumed they lived at the same address during pregnancy. We geocoded women's residences using ArcGIS 10.2[31] and excluded those who did not reside in Pennsylvania or whose address we were unable to geocode. We evaluated our assumption of mother's residential stability by comparing addresses in two Geisinger Health System datasets, 39 months apart (one from 2010 and the other from 2013), among 333,322 patients in both datasets. Due to strong collinearity between the unconventional natural gas development exposure metric and calendar year, we also excluded births prior to 2009 when little such activity had taken place in the study region.

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Birth outcomes

We extracted data from electronic health record files including labor and delivery notes and a separate labor and delivery database maintained continuously by nursing personnel. The clinician recorded gestational age as part of routine care based on patient-reported last menstrual period and 20 week ultrasound. We estimated the first day of pregnancy from gestational age. We studied four birth outcomes: term (≥ 37 week) birth weight, preterm birth (< 37 weeks gestation), low 5 minute Apgar score (< 7), and small for gestational age; we isolated moderate to late preterm birth (32-36 weeks gestation) in a sensitivity analysis. Infants with low 5 minute Apgar scores often require respiratory support and have poorer future academic achievement.[33] Small for gestational age was defined as less than the sex-specific 10th percentile of weight for each week of gestation within the Geisinger population from 2006-2013. While creating the *a priori* outcomes, we discovered that maternal and fetal specialists often use the electronic health record problem list to identify a pregnancy as high-risk. Because we hypothesized that UNGD could contribute to conditions (e.g., pulmonary, cardiovascular) that could designate a pregnancy as high-risk, p*ost hoc* we added high-risk pregnancy as an outcome.

Unconventional natural gas development activity index

We collected data, spanning 2005-2013, on well drilling and production dates and volumes from the Pennsylvania Department of Environmental Protection and on well stimulation dates and drilling depth from the Pennsylvania Department of Conservation and Natural Resources. We collaborated with SkyTruth (Shepherdstown, WV, skytruth.org) to use crowdsourcing to confirm well pad locations using U.S. Department of Agriculture aerial photographs. We imputed missing total depths, production volumes, and stimulation dates from available data. The assembled dataset included latitude and longitude of each well; dates of well spudding (i.e., beginning of drilling), perforation, stimulation, and production; total well depth; volume of natural gas produced; and the number of producing days annually. Because phases of unconventional natural gas development (i.e., pad development, drilling, stimulation, production) are known to differ by exposures and duration, we derived individual-level estimates to each of these four phases. Although there was heterogeneity by well, for the purposes of exposure assignment, we used published descriptions[34] of the process and information in our own data to estimate phase durations: (1) pad development = the 30 days prior to the first well drilled on a pad; (2) drilling = 1-30 days, based on total well depth; (3) hydraulic fracturing = 7 days; and (4) production = present when reported production values were non-zero.

We first created four exposure metrics by phase that incorporated all wells statewide as:

$$Mother \quad j \quad metric=\sum_{i=1}^{n}\sum_{k=1}^{l} m\left(I_A\left(k\right)\right)/{d_{ij}}^2$$

where n was the number pads or wells; k was the day with 1 equal to January 1, 2009 and l was equal to 1125 or January 31, 2013; m was 1 for pad and drilling, m was total well depth for stimulation (because we used total well depth as a surrogate for truck trips and hydraulic

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fracturing fluid volume), and m was gas volume for production (because we used production volume as a surrogate for air pollution emissions); $I_A(k)$ was 1 when the phase overlapped temporally with gestation; and d_{ij}^2 was the squared-distance between the coordinates of pad or well i and mother j's home address. The phase-specific units were pads/m^2, wells/m^2, total well depth (m)/m^2, and gas production volume m^3/m^2 for pad, drilling, stimulation, and production metrics, respectively. The denominator was always the squared-distance between wells and residences (m^2).

Because we wanted to estimate exposure to phases of unconventional natural gas development and there was collinearity between the four exposure metrics (ρ, 0.6-0.9), each was z-transformed then summed to estimate the unconventional natural gas development activity index (hereafter referred to as the activity index). This meant that a woman living close to several well pads under development, but far from any producing wells could have a similar index as a woman living near only producing wells. We did not evaluate trimester-specific indices because of very high inter-trimester correlations. We divided the aggregated activity index into quartiles for analysis.

Covariates

We included clinical, demographic, and environmental covariates to control for potential confounding based on *a priori* hypotheses and previous studies of birth outcome risk factors including neonate sex, gestational age (for birth weight), season and year of birth, maternal age, race/ethnicity, Geisinger primary care provider status, smoking status during pregnancy, pre-pregnancy body-mass index (BMI), parity, antibiotic orders during pregnancy, and receipt of Medical Assistance, a surrogate for low family socioeconomic status.[35,36] For teenagers ($\leq$20 years), we categorized pre-pregnancy BMI using z-scores based on U.S. Centers for Disease Control and Prevention data. Environmental covariates included distance to nearest major road (principal arterial and larger based on U.S. Census Bureau Topologically Integrated Geographic Encoding and Referencing road files),[24,37] community socioeconomic deprivation[38] and residential greenness (based on the average normalized difference vegetation index values in the 1250m × 1250m area surrounding the residence in the three seasons prior to delivery).[39] Due to concern about the potential contamination of ground water in the region, we used Pennsylvania Department of Environmental Protection public water service areas to assign household water source as municipal or well water.[12,40] Alcohol use was not a confounder, so was not included in adjusted models. We also did not adjust for blood pressure or the number of prenatal healthcare visits because we considered them potential mediators.

Statistical analysis

To assess the association of the activity index (quartiles) with birth outcomes, we fit a series of multilevel linear (for birth weight) and logistic (for other outcomes) regression models with random intercepts for mother and community to account for nesting of observations in women and place. The mother-specific intercept incorporated prior pregnancy outcomes (e.g., prior preterm birth) into our models. We selected final models by a combination of *a priori* hypotheses and likelihood ratio tests (P-value < 0.10). For each outcome, model 1 was adjusted for sex of the neonate and season of birth, maternal age at delivery (linear and

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quadratic, years), maternal race/ethnicity (white, black, Hispanic, other), primary care status (yes vs. no), smoking status during pregnancy (never, former, current, or conflicting/ missing), pre-pregnancy BMI (underweight: z-score > 2SD below mean or < 18.5 kg/m^2; normal: z-score within 1 SD of mean or 18.5-24.9 kg/m^2; overweight: z-score 1-2 SD above mean or 25-29.9 kg/m^2; or obese: z-score > 2 SD above mean or ≥ 30 kg/m^2), parity (nulliparous vs. multiparous), receipt of Medical Assistance (never vs. ever), delivery hospital (Geisinger Medical Center vs. Geisinger Wyoming Valley), distance to nearest major road in meters, drinking water source (well water vs. municipal), community socioeconomic deprivation (quartiles), and greenness (continuous). In model 2, we further adjusted associations for year (2009-2010 vs. 2011-2013). Birth weight models were also adjusted for gestational age (linear and quadratic, weeks) and high-risk pregnancy models were additionally adjusted for the average annual number of entries on the problem list to account for the fact that its use increased over time (mean of 14% more entries per year).

In sensitivity analyses we included the number of antibiotic orders during pregnancy, restricted preterm models to neonates born moderately to late preterm (32-36 weeks gestation), and fit a Cox proportional hazard model with gestational age as the timescale, preterm birth as the outcome, unconventional natural gas development varying by week, and robust standard errors. We also assessed the possibility of unobserved confounding by assigning babies born in 2006, before there was any unconventional natural gas development, the estimated exposure metric they would have accrued had they been born in 2012, when there was such development. If the 2012 unconventional natural gas development exposure metric were found to be associated with birth outcomes for these 2006 babies, it would suggest that our main study findings may have been spurious.

We report associations as difference in term birth weight or odds ratios for preterm birth, small for gestational age, 5-minute Apgar score, and high-risk pregnancy comparing ≥ quartile 2 of unconventional natural gas development activity to quartile 1 with 95% confidence intervals. Models did not exhibit residual spatial variation, which we checked for by visually inspecting semivariograms.[41] Because of the low proportion of missing data (0-1.4% on outcomes and 0-5.2% on confounders) and because missingness only appeared to be associated with year (more missing data in earlier years), patients were omitted from models when they were missing data. We used Stata version 13 (StataCorp. College Station, TX) and R version 3.0.0 (R Foundation for Statistical Computing).

RESULTS

We identified 20598 neonates born to 20569 mothers who delivered between 2006 and January 2013. After exclusions (Figure 1), we reached a final study sample of 9384 mothers who delivered 10496 neonates (mean of 1.2 per mother). Mothers lived in 699 communities (mean of 14 per community). In eTable 1 we compare the final population to those excluded. Geisinger patients had residential stability. We compared addresses from 2010 and 2013 on 333,222 patients and found that 79.8% had the exact same street address, 6.0% had moved <1500m and another 10% had moved 1500-16,000m from their original address.

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The mean birth weight was 3272 grams (SD = 612). Eleven percent (n = 1103) of the births were preterm, 8% were moderately preterm (n = 871), 2% (n = 227) had 5 minute Apgar scores < 7, 10% (n = 1024) were small for gestational age, as expected given our use of an internal standard, and 27% (n = 2853) of pregnancies were identified as high-risk (Table 1).

Unconventional natural gas development in the Pennsylvania Marcellus shale began in the southwest in 2005 (15 wells drilled) and quickly accelerated. By the period 2009-2012, an average of 1555 unconventional wells, drilled to an average depth of 3380m, and 1177 wells entered production annually (Figure 2). The mean (SD), median (IQR) number of wells within 20 km of mothers (during their pregnancy) in the first vs. fourth quartile of exposure to unconventional natural gas development was 6 (28), 0 (0-1) vs. 124 (202), 8 (1-122), respectively, reflecting a marked difference in intensity of potential exposure.

In Table 1 and 2 we present descriptive statistics of several demographic and clinical variables by UNGD activity quartile and by outcome. Neonates born in later years and in the summer and fall; and mothers that were multiparous, received an antibiotic order during pregnancy, used well water, or lived farther from the nearest major road appeared to have higher exposure to unconventional natural gas development activity. Among those with poor pregnancy outcomes, several covariates were more common including receipt of Medical Assistance, black race/ethnicity, ever-smoking, and others (Table 2). Mothers with a primary care provider had an average of 16 prenatal visits (SD = 6) compared to 12 (SD = 7) in those without.

The activity index was not associated with adverse birth outcomes in unadjusted analyses (Table 1). In adjusted birth weight and preterm models, current smoking, underweight BMI, nulliparity, high community socioeconomic deprivation (preterm only), and black race/ethnicity and receipt of Medical Assistance (birth weight only) were positively associated; normal BMI, never smoking, farther distance to nearest major road, and higher residential greenness (preterm only) were negatively associated.

After adjustment for covariates, the fourth quartile of the activity index was associated with lower term birth weight, but not after further adjustment for year (Table 3). In adjusted models, the odds of preterm birth increased across quartiles of the activity index (fourth vs. first quartile, 1.4 [95% CI: 1.0-1.9]) (Table 3). This association strengthened with adjustment for year (Table 3), persisted in a survival model framework (eTable 2), and was robust to restriction to moderate and late preterm births (fourth vs. first quartile, OR = 1.5 [95% CI = 1.0-2.4]). In model 2, antibiotic orders were associated with preterm birth (OR = 1.5 [95% CI = 1.3-1.6]). Unconventional natural gas development exposure during the prenatal period was associated with high-risk pregnancy (fourth vs. first quartile of the activity index, OR = 1.3 [95% CI: 1.1-1.7]), but not with 5 minute Apgar score or small for gestational age (results not shown).

In a sensitivity analysis in infants born in 2006 (n = 1932), future exposure to unconventional natural gas development was not associated with preterm birth, Apgar score, or small for gestational age birth in fully adjusted models. Neonates born in 2006, who

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would have been in the 4th quartile of the activity index had they been born in 2012, had lower birth weights ($\beta = -53$ [95% CI −120 to 12]).

DISCUSSION

We used electronic health record data to conduct a population-based retrospective cohort study in central and northeast Pennsylvania during a time of very rapid unconventional natural gas development in the region. Our study examined associations between prenatal exposure to unconventional natural gas development activity and four birth outcomes and high-risk pregnancy in the mother. We demonstrated that mothers with higher activity index values during pregnancy were more likely to give birth preterm, a finding corroborated in time-to-delivery analysis, and to have a physician-recorded high-risk pregnancy. An association with term birth weight was not robust to adjustment for year. In a sensitivity analysis, when we assigned babies born in 2006 the activity index they would have had if they were born in 2012, unconventional natural gas development was associated with lower birth weight, suggesting that the primary association may have been due, at least in part, to unobserved confounding. There were no associations with Apgar score or small for gestational age. The electronic health record allowed us to carefully ascertain both pregnancy outcomes and confounding variables. We were able to control for other community conditions and exposures, including distance to roadways, source of drinking water, and community socioeconomic deprivation. To our knowledge, this is also the first study to base estimates of unconventional natural gas development activity exposure in relation to health risks on four separate phases of well development.

Three recent reviews summarized evidence linking health and unconventional natural gas development and found it lacking.[1-3] Werner et al. identified only four highly relevant peer-reviewed studies related to these processes and health outcomes: two using self-reported symptoms, one of childhood cancer that may not have adequately accounted for latency, and one of birth outcomes.[21,22,26,30] The only published study dealing with birth outcomes reported that density and proximity of gas wells in Colorado, USA, were associated with two birth defects, but also higher birth weight and lower odds of preterm birth.[26] During the study period, the U.S. Energy Information Administration reported that Colorado produced 28 million cubic meters of natural gas unconventionally and 130 million cubic meters conventionally. We were able to study people living in areas with much higher unconventional natural gas development activity; Pennsylvania produced 58 billion cubic meters of natural gas unconventionally in 2012. A second, unpublished study, compared neonates born to mothers residing within 2.5 km of a spudded well to those living within 2.5 km of a permitted, but not spudded, well.[27] This study reported decreased term birth weight (but did not control for gestational age) and increased small for gestational age and 5 minute Apgar scores < 8, but no association with preterm birth. We too observed associations with Apgar scores < 8, but not < 7, as most prior studies have used, and between unconventional natural gas development and term birth weight when we omitted gestational age.

The unconventional natural gas development process is associated with heterogeneous exposures that last varying amounts of time. We did not have the capability to measure exposures directly. However, we were able to account for the varying durations of the

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different phases by using published descriptions and information from our own analysis to assign deliveries activity values in defined windows. This should be an improvement over prior studies, which generally used spud date to identify the start of an exposure assumed to last forever, an incorrect assumption.[26,30] Any bias introduced by errors in the estimation of the durations of development phases is likely to be independent of birth outcomes and thus tend to bias associations towards the null.

There are multiple ways unconventional natural gas development activity could influence birth outcomes. Concerns include impacts on air quality,[1-3] ground and surface water quality,[12] and maternal psychosocial stress from noise, increased traffic volumes, and contextual exposures including social disruption and community livability.[4] For many of these, their associations with birth outcomes have been investigated in other settings.[14,17,37,42] For instance, prior literature suggests that a $10\mu g/m^3$ increase in exposure to $PM_{2.5}$ is associated with a 10% increase in odds of preterm birth and low birth weight.[15,18] There are also several proposed mechanisms linking PM exposure to preterm birth including interference with placental development, inflammation, and increased risk of infection.[18] In our study, mothers with higher activity indices were indeed more likely to receive an antibiotic order during their pregnancy. Neighborhood contextual factors have also been consistently associated with birth outcomes.[43] Women living in communities exposed to unconventional natural gas development likely experience both environmental and social exposures that may have synergistic effects on health.[44] Finally, unmeasured confounding could have contributed to our results; our measure of family SES was binary and did not include education, and we also had no information on occupation.

This study had limitations. In an effort to assign activity values more accurately than prior studies, we estimated the duration of each phase of unconventional natural gas development. This is likely to have introduced measurement error since the amount of time each phase lasts varies by well. We used a distance-based metric to estimate exposure to four phases of development, but were not able to evaluate phase-specific associations due to collinearity. Phases are known to contribute different types of exposures (e.g., pad development is a source of diesel emissions including PM as well as noise),[1] but our methodology did not allow us to differentiate among phase-specific exposures, type of hazardous exposure (e.g., air and water pollution), and the contextual effects of development. We were not able to take environmental samples, which may have led to exposure misclassification and prevented us from determining if a specific pollutant was responsible for our associations. Additionally, unconventional natural gas development was highly correlated with year, making it challenging to control for temporal trends; therefore we presented results both unadjusted and adjusted for year. In regards to conventional gas development in the state, although the densest development is in the northwest and many of these wells are decades old and non-producing, there was still collinearity between our activity index and conventional gas proximity metrics, which precluded adjustment for conventional gas well locations. Historical addresses are not retained in the Geisinger electronic health record so we were not able to determine whether the last recorded address represented residential location during the course of pregnancy. Our sensitivity analysis suggested that most Geisinger patients do not move, and if they do, they tend to move locally. In our study, many wells were developed in one location over time, so the exposures, emissions, and community

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circumstances present in one trimester were likely present in another. This collinearity prevented us from evaluating trimester-specific associations.

Prior studies found elevated symptoms in regions with unconventional natural gas development and concern by residents of possible health effects. This study adds to limited evidence that unconventional natural gas development adversely affects birth outcomes. We observed that an index of development activity was associated with both preterm birth and high-risk pregnancy. Multiple aspects of development might be involved, including hazardous exposures and contextual effects. Future studies should use direct environmental sampling to more accurately capture exposure and include data on mother's place of residence throughout pregnancy. Such data is needed to allow policy makers to effectively weigh the risks and benefits of unconventional natural gas development.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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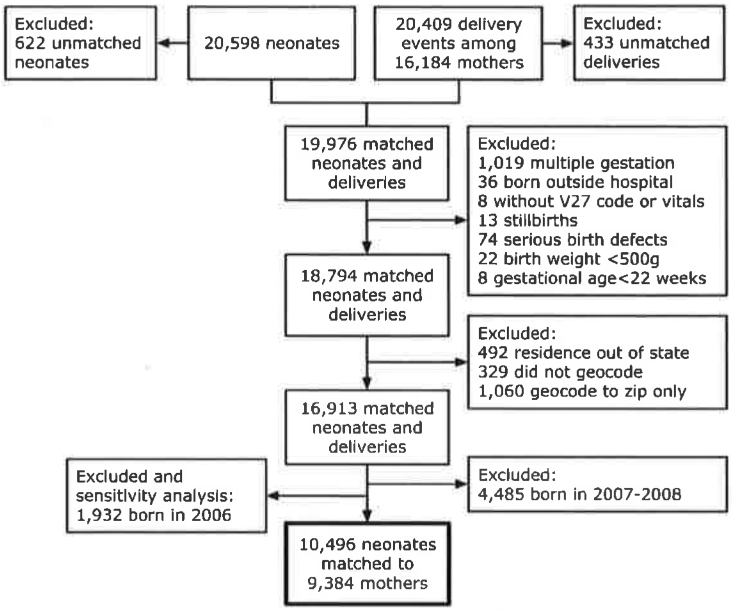

Figure 1.
Flow diagram of study population assembly

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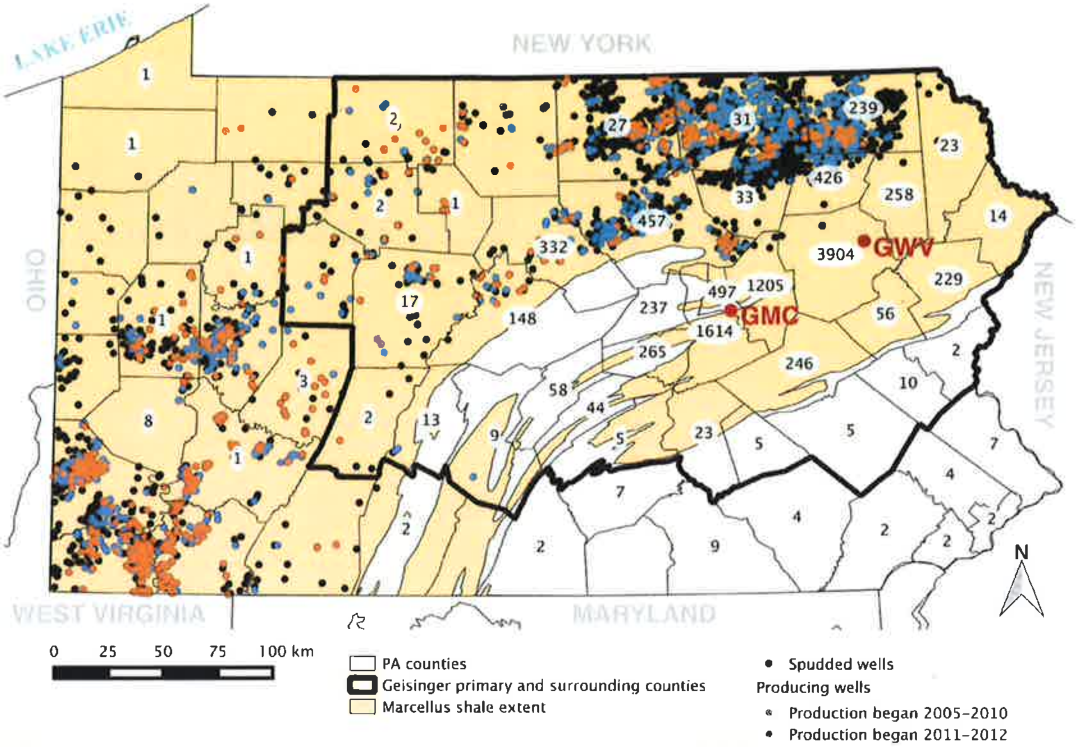

Figure 2.

The Marcellus shale extent, the location of spudded and producing wells as of December 2012, the location of the two Geisinger Health System hospitals and the primary and surrounding Geisinger counties. Annotation indicates the number of neonates born to mothers residing in each county. GMC = Geisinger Medical Center. GWV = Geisinger Wyoming Valley.

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Table 1

Distribution of study population characteristics among 9384 mothers and their 10496 children by quartile of unconventional natural gas development (UNGD) activity index

		UNGD activity index quartile[a]			
Variable	**No. (%)**	**1**	**2**	**3**	**4**
Maternal characteristics					
Age at birth, years, mean (SD)	10496 (100)	27.6 (5.8)	27.8 (5.7)	27.9 (5.7)	27.8 (5.8)
Race/ethnicity, %					
White	9327 (89)	88	89	86	92
Black	382 (4)	4	3	4	3
Hispanic	601 (6)	6	6	7	3
Other	148 (1)	2	1	2	1
Missing	38 (<1)	<1	<1	<1	<1
Primary care patient, %	4789 (46)	45	45	46	46
Smoking status[b], %					
Never	4984 (47)	46	45	49	49
Former	2258 (22)	21	24	21	20
Current	1785 (17)	18	18	15	17
Conflicting or missing	1489 (14)	15	13	15	14
Alcohol use during pregnancy[b], %					
No	8448 (80)	77	79	83	83
Yes	1412 (13)	14	14	13	13
Missing	636 (6)	9	7	4	4
Pre-pregnancy body-mass index (kg/m^2), %					
<18.5	222 (2)	2	2	2	2
18.5-24.9	3878 (37)	37	38	36	36
25-29.9	2834 (27)	27	25	28	28
≥30	3013 (29)	29	30	28	28
Missing	549 (5)	5	5	5	5
Pre-pregnancy blood pressure, %					
Systolic >140mmHg or diastolic >90mmHg	1125 (11)	9	11	13	10
Normal	9371 (89)	91	89	87	90
Nulliparous, %	4600 (44)	47	43	44	41
Healthcare visits during pregnancy, n, mean (SD)	10496 (100)	14.4 (6.3)	13.8 (6.4)	13.6 (6.7)	13.7 (6.7)
Antibiotic order during pregnancy, %	3338 (32)	30	31	31	35
Receipt of Medical Assistance, %	4796 (46)	44	47	45	47
Delivery hospital, %					
Geisinger Medical Center	5638 (54)	57	57	51	49

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		UNGD activity index quartile[a]			
Variable	**No. (%)**	**1**	**2**	**3**	**4**
Geisinger Wyoming Valley	4858 (46)	43	43	49	51
Distance to nearest major road, m, median (IQR)	10496 (100)	788 (284-2825)	863 (304-3229)	609 (237-1826)	1373 (455-6757)
Drinking water source, %					
Municipal water	7306 (70)	72	72	78	57
Well water	3190 (30)	28	28	22	43
Community socioeconomic deprivation[c], %					
Quartile 1	2590 (25)	25	23	24	27
Quartile 2	2648 (25)	23	22	23	28
Quartile 3	2642 (25)	25	23	24	29
Quartile 4	2616 (25)	27	33	29	15
Residential greenness, NDVI index, mean (SD)	0.54 (0.10)	0.50 (0.11)	0.56 (0.09)	0.54 (0.09)	0.54 (0.11)
Infant Characteristics					
Male, %	5372 (51)	51	52	52	50
Birth weight, grams, mean (SD)	10495 (100)	3289 (604)	3249 (623)	3286 (599)	3264 (622)
Gestational age, weeks, mean (SD)	10418 (99)	38.9 (2.2)	38.9 (2.4)	39.0 (2.1)	38.9 (2.3)
Preterm birth <37 weeks, %	1103 (11)	10	11	10	11
Preterm birth 32 to 36 weeks, %	871 (8)	2	2	2	2
Small for gestational age, %	1024 (10)	9	10	10	10
Apgar score, %					
5 minute, <7	227 (2)	2	2	2	2
5 minute, ≥7	10199 (95)	97	97	97	97
5 minute, missing	70 (<1)	1	<1	1	1
High-risk pregnancy[d], %	2853 (27)	17	25	33	33
Birth year, %					
2009	2336 (22)	79	7	1	2
2010	2518 (24)	20	55	9	11
2011	2608 (25)	1	27	49	22
2012	2852 (27)	<1	11	38	60
2013	182 (2)	0	<1	2	5
Birth season, %					
December-February	2562 (24)	27	20	25	24
March-May	2605 (25)	29	25	24	21
June-August	2748 (26)	23	29	25	27
September-November	2581 (25)	20	26	25	27

UNGD activity index quartile was assigned based on 4 z-transformed indicators using inverse-distance squared models that incorporated distance to the mother's home; dates and durations of the phases (well pad development, spudding, hydraulic fracturing, and production); and well characteristics (depth and production volume) during gestation, and is in standard deviation units. Percentages are rounded to whole numbers.

EHR = electronic health record. IQR = interquartile range. NDVI = normalized difference vegetation index.

[a] Quartile 1: <−0.44; Quartile 2: −0.43 to −0.15, Quartile 3: −0.14 to 0.18, Quartile 4: >0.18.

[b] Smoking, alcohol use, and high-risk pregnancy were reported during pregnancy in the EHR social history and problem list.

[c] Community socioeconomic deprivation was assigned at the township, borough, or census tract level, based on 6 indicators derived from the U.S. Census American Community Survey 2012 5-year estimates: combined less than high school education, not in the labor force, in poverty, on public assistance, civilian unemployment, and does not own a car; a higher score represents a more deprived community.

[d] Defined based on physician-reported high-risk pregnancy.

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Table 2

Distribution of outcomes by selected covariates

	Outcome				
	Birth weight, g, median (IQR)	**Preterm birth, n (%)**	**5 min Apgar <7, n (%)**	**SGA, n (%)**	**High risk pregnancy[a], n (%)**
N	10495	1103	10426	1024	2853
Pre-pregnancy body-mass index (kg/m^3)					
<18.5	3051 (2696-3359)	50 (23)	7 (3)	41 (19)	66 (30)
18.5-24.9	3258 (2903-3575)	408 (11)	80 (2)	443 (12)	1008 (26)
25-29.9	3352 (2991-3685)	265 (9)	66 (2)	267 (10)	751 (26)
≥30	3404 (3071-3745)	286 (10)	57 (2)	222 (7)	940 (31)
Missing	3263 (2908-3631)	94 (17)	17 (3)	51 (10)	89 (16)
Parity					
Nulliparous	3303 (2940-3625)	486 (11)	116 (2)	525 (12)	981 (21)
Multiparous	3338 (2991-3686)	617 (10)	111 (2)	499 (9)	1872 (32)
Antibiotic order during pregnancy					
No	3348 (3012-3679)	580 (8)	131 (2)	686 (10)	1891 (26)
Yes	3268 (2885-3617)	523 (16)	96 (3)	338 (10)	962 (29)
Year of birth					
2009 and 2010	3330 (2974-3665)	528 (11)	90 (2)	455 (10)	888 (18)
2011, 2012, and 2013	3314 (2968-3657)	575 (10)	138 (2)	569 (10)	1965 (35)
Delivery hospital					
Geisinger Medical Center	3284 (2884-3630)	874 (16)	180 (3)	554 (10)	1507 (27)
Geisinger Wyoming Valley	3365 (3050-3688)	229 (5)	47 (1)	470 (10)	1346 (28)
Community socioeconomic deprivation [b]					
Quartile 1	3372 (3033-3700)	249 (10)	67 (3)	205 (8)	597 (23)
Quartile 2	3345 (2984-3667)	264 (10)	49 (2)	241 (9)	705 (27)
Quartile 3	3303 (2944-3640)	306 (12)	53 (2)	262 (10)	727 (28)
Quartile 4	3264 (2925-3620)	284 (11)	58 (2)	316 (12)	824 (32)

Percentages are rounded to whole numbers.

EHR = electronic health record. IQR = interquartile range. SGA = small for gestational age.

[a] Reported in EHR problem list during pregnancy.

[b] Community socioeconomic deprivation was assigned at the township, borough, or census tract level, based on 6 indicators derived from the US Census American Community Survey 2012 5-year estimates: combined less than high school education, not in the labor force, in poverty, on public assistance, civilian unemployment, and does not own a car; a higher score represents a more deprived community.

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Table 3

Associations of term birth weight and preterm birth and exposure to unconventional natural gas development (UNGD) activity

	Model 1A[a]	Model 2A[b]	Model 1B[c]	Model 2B[d]
	Term birth weight (g)		Preterm birth	
Variable	**Difference (95% CI)**	**Difference (95% CI)**	**OR (95% CI)**	**OR (95% CI)**
UNGD activity quartile	N = 8839	N = 8839	N = 9848	N = 9848
1	Reference	Reference	1.0	1.0
2	−21 (−46 to 5)	−16 (−44 to 11)	1.2 (0.9-1.6)	1.3 (1.0-1.8)
3	−9 (−35 to 16)	1 (−34 to 36)	1.3 (1.0-1.7)	1.6 (1.1-2.4)
4	−31 (−57 to -5)	−20 (−56 to 16)	1.4 (1.0-1.9)	1.9 (1.2-2.9)
Year of birth				
2009 or 2010		Reference		1.0
2011, 2012, or 2013		12 (−15 to 39)		1.3 (1.0-1.8)

CI=confidence interval. OR = odds ratio.

[a] Model 1A was adjusted for sex and gestational age of neonate; maternal characteristics: age at delivery, race/ethnicity, primary care patient status, smoking status, pre-pregnancy body mass index, parity, number of antibiotic orders during pregnancy, receipt of Medical Assistance, delivery hospital, drinking water source, distance to nearest major road, mean residential greenness during pregnancy; and community socioeconomic deprivation quartile.

[b] Model 2A further adjusted for year of birth.

[c] Model 1B was adjusted for sex of neonate; maternal characteristics: age at delivery, race/ethnicity, primary care patient status, smoking status, pre-pregnancy body mass index, parity, receipt of Medical Assistance, delivery hospital, drinking water source, distance to nearest major road, mean residential greenness during pregnancy; and community socioeconomic deprivation quartile.

[d] Model 2B further adjusted for year of birth.

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Residential Proximity to Oil and Gas Development and Birth Outcomes in California: A Retrospective Cohort Study of 2006–2015 Births

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BACKGROUND: Studies suggest associations between oil and gas development (OGD) and adverse birth outcomes, but few epidemiological studies of oil wells or inactive wells exist, and none in California.

OBJECTIVE: Our study aimed to investigate the relationship between residential proximity to OGD and birth outcomes in California.

METHODS: We conducted a retrospective cohort study of 2,918,089 births to mothers living within 10 km of at least one production well between January 1, 2006 and December 31, 2015. We estimated exposure during pregnancy to inactive wells count (no inactive wells, 1 well, 2–5 wells, 6+ wells) and production volume from active wells in barrels of oil equivalent (BOE) (no BOE, 1–100 BOE/day, >100 BOE/day). We used generalized estimating equations to examine associations between overall and trimester-specific OGD exposures and term birth weight (tBW), low birth weight (LBW), preterm birth (PTB), and small for gestational age birth (SGA). We assessed effect modification by urban/rural community type.

RESULTS: Adjusted models showed exposure to active OGD was associated with adverse birth outcomes in rural areas; effect estimates in urban areas were close to null. In rural areas, increasing production volume was associated with stronger adverse effect estimates. High (>100 BOE/day) vs. no production throughout pregnancy was associated with increased odds of LBW [odds ratio (OR) = 1.40, 95% confidence interval (CI): 1.14, 1.71] and SGA (OR = 1.22, 95% CI: 1.02, 1.45), and decreased tBW (mean difference = −36 grams, 95% CI: −54, −17), but not with PTB (OR = 1.03, 95% CI: 0.91, 1.18).

CONCLUSION: Proximity to higher production OGD in California was associated with adverse birth outcomes among mothers residing in rural areas. Future studies are needed to confirm our findings in other populations and improve exposure assessment measures. https://doi.org/10.1289/EHP5842

Introduction

Oil and gas development (OGD) by the U.S. petroleum industry spans decades in many states but concern about its potential health and equity impacts did not gain traction among researchers until the recent rapid increase in hydraulic fracturing (HF) (Finkel and Law 2011; Kovats et al. 2014; Mitka 2012). As of 2017, California (CA) was one of the top five producers of crude oil in the country (U.S. EIA 2018a, 2018b). Four of the 10 largest U.S. oil fields are in CA's San Joaquin and Los Angeles Basins (Long et al. 2015a), and unlike newer shale gas plays, most of CA's natural gas is extracted from reservoirs also producing oil (Long et al. 2015b). Given the long history of OGD in CA, stimulation techniques, such as water and steam injection and HF, are primarily used at established sites rather than newly drilled wells. Oil recovered via water flooding and steam injection (conventional enhanced oil recovery methods) accounted for 76% of the state's oil production in 2009 (Long et al. 2015b), whereas HF, an unconventional stimulation technique, accounted for 20% of CA's oil production in the last decade. Due to types of geological formations, HF practices in CA differ from other states, potentially resulting in differing environmental hazards (Long et al. 2015b). OGD production in CA also occurs in both rural and urban settings in comparison with other states, such as rural Pennsylvania and Colorado, where many epidemiological studies have been conducted (Casey et al. 2015; Currie et al. 2017; Hill 2018; McKenzie et al. 2014; Rasmussen SG et al. 2016; Tustin et al. 2017). Therefore, an epidemiological study of the relationship between adverse birth outcomes and OGD in CA, a state with a diverse population and the most annual births of any U.S. state, can provide insights about the potential health impacts of OGD exposure in both rural and urban areas.

Characterizing exposures related to OGD poses significant measurement challenges because multiple environmental hazards are associated with different stages of extraction and production. OGD involves the development of oil and gas sites and wells (production and injection for enhanced recovery), transport of materials to and from well sites, drilling, operation of equipment to recover oil and gas, and collection and disposal of chemicals and waste separated from the raw oil and gas (Long et al. 2015a). These activities are associated with diverse environmental hazards, including air and water pollutants, noise, odors, excessive and inappropriate lighting, and undesired land use changes (Adgate et al. 2014; Long et al. 2015a). The application of unconventional techniques presumably enhances the environmental burdens because the additional toxic chemicals that are used can potentially be released into air, water, and soil (Adgate et al. 2014; Long et al. 2015a; Macey et al. 2014; Roy et al. 2014; Vengosh et al. 2014).

Air pollutants associated with OGD include particulate matter (PM) with an aerodynamic diameter of $<2.5\ \mu m$ ($PM_{2.5}$), diesel PM, nitrogen oxides (NO_x), secondary ozone formation, mercury, and volatile organic compounds (VOCs) like benzene, toluene, ethylbenzene and xylene (BTEX) from truck traffic, drilling, hydraulic fracturing, production, and flaring (Allshouse et al. 2019; Brantley et al. 2015; Colborn et al. 2014; Eapi et al. 2014; Esswein et al. 2014; Franklin et al. 2019; Goetz et al. 2015; Koss et al. 2017; Lan et al. 2015; Macey et al. 2014; Marrero et al. 2016; Maskrey et al. 2016; Mellqvist et al. 2017; Roy et al. 2014; Warneke et al. 2014). Additionally, fugitive toxic air contaminants c
head (Garcia-Gonzales et al. 2019; Warneke
affect health near the points of release.

CA
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associated with OGD include gas-phase hydrocarbons, chemicals mixed in drilling fluids, and naturally occurring salts, metals, and radioactive elements within shale that surface with wastewater along with recovered oil and gas and that can contaminate potable water via leaks and spills or evaporate (Adgate et al. 2014; Hildenbrand et al. 2015; Long et al. 2015a; Vengosh et al. 2014). Noise pollution is associated with well pad construction, truck traffic, drilling, pumps, flaring of gases, and other processes (Allshouse et al. 2019; Blair et al. 2018; Ebisu and Bell 2012; U.S. BLM 2006). Drilling and production activities occur both during the daytime and nighttime, and light pollution has been previously reported as a nuisance in communities undergoing unconventional OGD (Long et al. 2015a), suggesting OGD may affect the health of nearby communities via increased psychosocial stress.

Several OGD-related environmental exposures have been linked to reduced birth weight and gestational age: air pollution, e.g., $PM_{2.5}$, NOx, SOx (Basu et al. 2014; Dadvand et al. 2013, 2014; Ebisu and Bell 2012; Long et al. 2015a; Morello-Frosch et al. 2010; Ponce et al. 2005; Ritz et al. 2007); noise pollution (Arroyo et al. 2016; Gehring et al. 2014); some of the chemical compounds found in OGD wastewater (Long et al. 2015a; Valero de Bernabé et al. 2004); and psychosocial distress (Dominguez et al. 2008; Goldenberg et al. 2008; Rondó et al. 2003; Valero de Bernabé et al. 2004). Previous studies examining the relationship between unconventional OGD and birth outcomes provide suggestive evidence of adverse effects. Although study designs vary, most have characterized OGD exposure based on the density and distance of HF shale gas wells near the maternal residence in urban and rural Colorado (McKenzie et al. 2014, 2019), Pennsylvania (Casey et al. 2015; Currie et al. 2017; Hill 2018; Ma 2016; Stacy et al. 2015), Oklahoma (Janitz et al. 2019), and urban Texas (Walker Whitworth et al. 2018, 2017). Among the 10 studies, 8 evaluated our outcomes of interest. Some studies found greater exposure to OGD was associated with reductions in term birth weight (tBW) (Hill 2018; Stacy et al. 2015) and increased odds or incidence of low birth weight (LBW) (Currie et al. 2017; Hill 2018), preterm birth (PTB) (Casey et al. 2015; Walker Whitworth et al. 2018, 2017), and small for gestational age births (SGA) (Hill 2018; Stacy et al. 2015). However, those studies also reported statistically insignificant (Casey et al. 2015; Whitworth et al. 2017) or inverse associations (McKenzie et al. 2014; Stacy et al. 2015) for some birth outcomes.

Building on this research, our study focused on OGD in CA. We conducted our analysis in regions where OGD is concentrated: the Sacramento Valley, San Joaquin Valley, South Central Coast, and South Coast air basins. To our knowledge, our retrospective cohort study with births from 2006–2015 is the first to evaluate prenatal OGD exposure from oil as well as gas wells, inactive as well as active wells, and non-HF and HF wells in rural and urban settings of CA.

Methods

Study Population

Birth records for 1 January 2006 to 31 December 2015 were obtained from the California Department of Public Health (CDPH). CDPH collects statewide birth records that include mother's residential address at the time of birth, which we geocoded to assign exposure to OGD exposure and area-level covariates using ArcGIS (ESRI). Births with missing street-level addresses or that could not be successfully geocoded after a manual cleaning of the address fields for spelling and punctuation errors were excluded (5%). We selected the Sacramento Valley, San Joaquin Valley, South Central Coast, and South Coast air basins because they had the highest well densities in CA between 2005 and 2015 (Figure S1). We illustrate the construction of the study population in Figure 1. Exclusion criteria included missing last menstrual period (LMP) date, which was approximated as the date of conception and used to estimate gestational age (3%); congenital anomalies or abnormal birth conditions such as cleft lip and Down's syndrome (4%); plural births, e.g., twins, triplets (4%); implausible birth weights of less than 500 g or greater than 5,500 g (4%) (Alexander et al. 1996; Padula et al. 2014; Ponce et al. 2005; Talge et al. 2014); and implausible gestational ages of less than 22 or greater than 44 wk (4%) (Alexander et al. 1996; Talge et al. 2014). To limit unmeasured confounding and enhance comparability of exposed and unexposed populations, we also excluded births to mothers who did not live within 10 km of at least one oil/gas production well (3%). Finally, we excluded observations with any missing covariates or outcomes (2%) to arrive at a final study population of 2,918,089 births ($N = 2,718,629$ term births). All study protocols were approved by the Institutional Review Board of the CA Department of Public Health (#13-05-z) and the University of California, Berkeley (# 2013-10-5,693).

Birth Outcomes

We assessed the relationship between OGD and four outcomes: *a*) continuous birth weight (grams) among tBW (≥37 completed weeks); *b*) LBW (<2,500 g); *c*) PTB (<37 wk); and *d*) SGA (birth weight less than the U.S. sex-specific 10th percentile of weight for each week of gestation (Talge et al. 2014). Gestational age was estimated by subtracting the LMP date from the date of birth.

Exposure Assessment

Active and inactive oil and gas well records including monthly production data were downloaded from the CA Division of Oil, Gas and

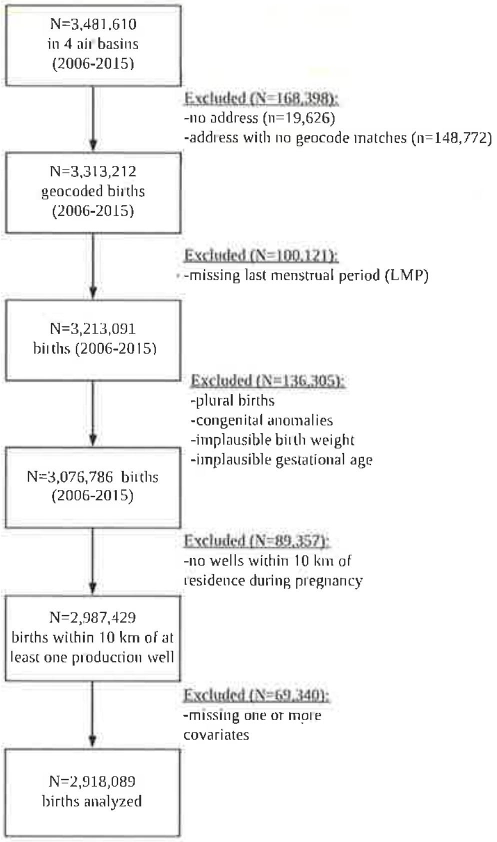


Figure 1. Flow diagram of study population development and exclusion criteria applied.

Geothermal Resources website (CA DOGGR) in December 2015 (the division has been renamed to the CA Geologic Energy Management Division, CalGEM, as of January 2020). We assessed exposure to inactive wells because previous studies have found fugitive methane emissions from abandoned production wells that have not been plugged or were improperly plugged (Boothroyd et al. 2016; U.S. EPA 2018; Kang et al. 2016). VOCs, such as BTEX and toxic air contaminants, are likely coemitted with methane (LACDPH 2018; SCAQMD 2019), and exposure to VOCs, including BTEX and formaldehyde, are associated with adverse birth outcomes (Bolden et al. 2015; Chang et al. 2017; Maroziene and Grazuleviciene 2002). Some of the 224,695 wells in the data set began producing as far back as 1900. The DOGGR data included well latitude/longitude and monthly production volume (barrels of oil and/or cubic meters of natural gas). We defined a production well as active if it produced at least one unit of oil or gas in a given month; production wells could transition between active and inactive status across the study period. We combined these well data with mothers' residential addresses at the time of delivery, date of conception (defined as LMP), and date of delivery to assign prenatal exposure to oil and gas wells.

Study participants lived within 10 km of at least one active or inactive well at the time of delivery. We classified women who had at least one active or inactive well within 1 km of their residential address as exposed (Figure 2); prior literature suggests highest exposure to OGD-related hazards within this radius (Boyle et al. 2017; McKenzie et al. 2012; Meng 2015; Walker Whitworth et al. 2018, 2017). We selected the 1-km buffer presuming that localized air pollution is likely the greatest contributor to OGD-related exposure in CA. We used the short distance to minimize the impact of dispersion and the contribution of exposure from other sources of air pollution. We calculated exposure across the entire pregnancy and by trimester to examine potential critical windows of prenatal exposure.

Exposure to active wells was characterized by oil and gas production volume during pregnancy and exposure to inactive wells by well count. Total production volume exposure from active wells within 1 km was derived by summing monthly barrels of oil and

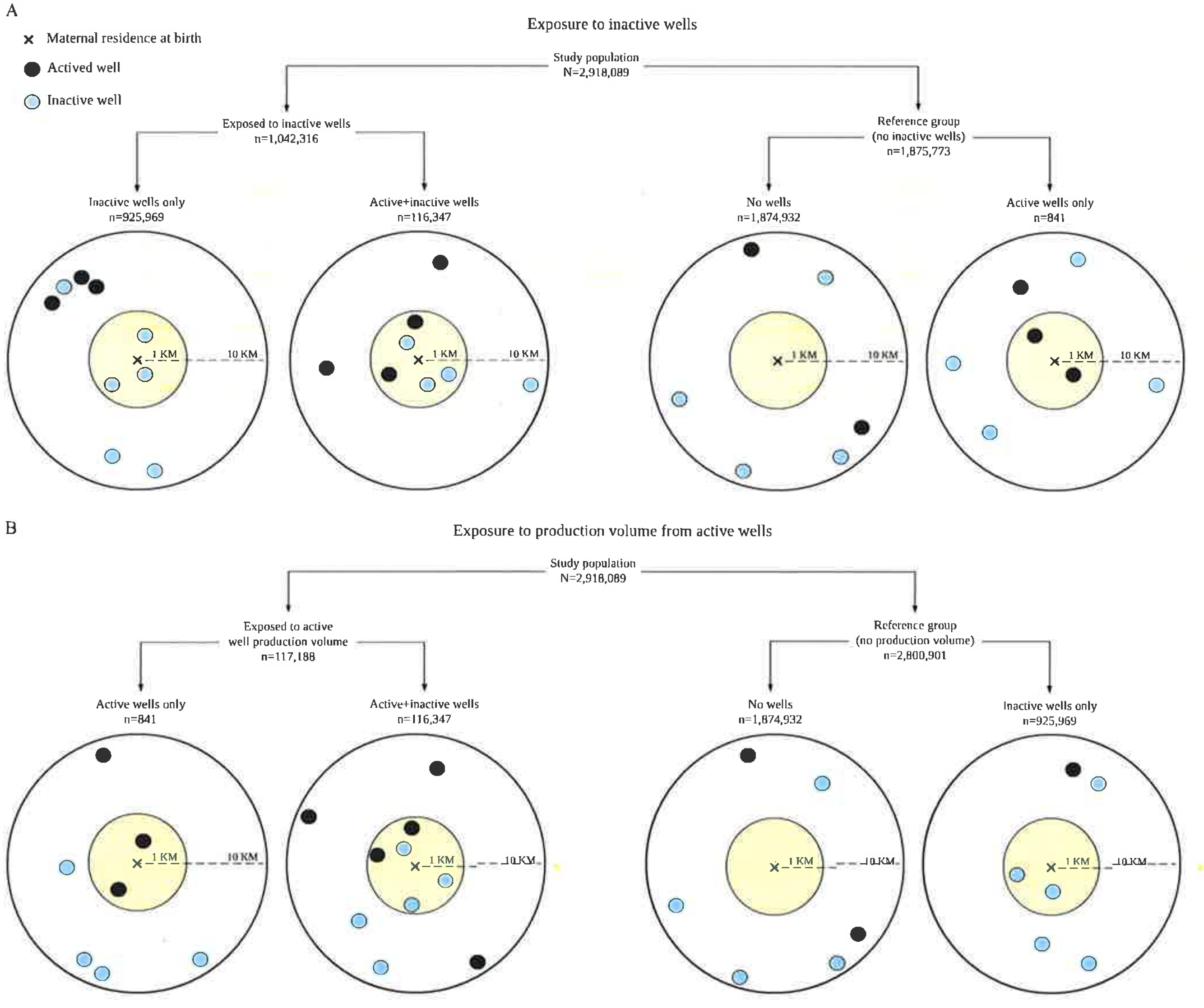


Figure 2. Schematic of definition of exposure and reference groups for inactive well count (A) and active well production volume (B). For each exposure metric, exposure was based on the presence of inactive or active wells within the 1 km buffer. Observations without the specific well type for each metric were assigned into the reference category.

barrels of oil equivalent (BOE) of natural gas. Production volume from oil and gas wells were summed because 95% of gas wells also produced oil (i.e., wet gas) and gas-only wells did not produce significant amounts of gas. Production volume was summed as shown in Equation 1:

$$\text{Total production volume}_j = \sum_{i=1}^{n}\sum_{k=k}^{l}\text{Prod(oil)}_{ik} + \sum_{i=1}^{n}\sum_{k=k}^{l}\text{Prod(gas)}_{ik}/6,$$

where Prod(oil)_{ik} was the production volume of oil (in barrels), and Prod(gas)_{ik} was the production volume of gas (in thousand cubic feet, mcf) at well i during month and year k of mother j's entire pregnancy or trimester. K is the month and year of conception or beginning of a trimester, and l is the month and year of delivery or end of a trimester. K has a minimum value of 1 equal to January 2005, and l has a maximum of 124 or December 2015. Gas production volume was converted from the original units to BOE by dividing by 6 because 6,000 cubic feet (mcf) = 1 BOE (Bonavista Energy Corporation 2018; Schmoker and Klett 2005). The total production volume for the first and last month of the entire pregnancy or trimester was also weighted by the proportion of the month the mother was pregnant.

We calculated the number of inactive wells within 1 km of a mother's residence during her pregnancy by subtracting the number of active wells from the total number of wells within 1 km. For analysis, we first normalized production volume by the number of days of the entire pregnancy or within each trimester by dividing production volume by the total number of days and then categorized exposure to production volume of active wells based on the exposure distribution as: *a*) no active wells, *b*) 1–100 BOE/d (moderate), and *c*) more than 100 BOE/d (high). We similarly categorized exposure to inactive wells as: *a*) no inactive wells, *b*) 1 inactive well, *c*) 2–5 inactive wells, and *d*) 6 or more inactive wells. The production volume was normalized to prevent bias from neonates born later because their exposure period was longer. Given a lack of *a priori* knowledge about the production volume or inactive well count that might constitute a harmful exposure, we selected these categories based on the distribution of each exposure metric across cases and noncases to ensure sufficient overall sample size and number of cases in each exposure group. The exposure variables were not modeled as continuous because the distribution was right skewed (Table S2). Both active and inactive well exposure variables were included in all regression models. The exposure variables were generated in R version 3.3.1 (R Development Core Team).

Covariates

Individual-level covariates that were identified *a priori* as significant predictors of our outcomes and potential confounders based on prior studies were derived from the CDPH birth records. Infant covariates included sex, month (categorical) of birth, and year of birth (categorical) to control for seasonal and secular trends. Maternal covariates included age in years (<20, 20–24, 25–29, 30–34, 35+), race/ethnicity (non-Hispanic white, black, American Indian, Asian-Pacific Islander, unknown or other, and Hispanic), educational attainment (<high school, high school graduate/GED, some college, college+), Kotelchuk index of prenatal care (inadequate, intermediate, adequate, adequate+) (Alexander and Kotelchuck 1996; Kotelchuck 1994), and parity (nulliparous vs. multiparous). For maternal race/ethnicity, American Indian, unknown, and other were combined into one category due to the small number of women in each group. We included mean-centered and mean-centered squared variables for gestational age in the tBW model to allow for nonlinearity.

We also integrated area-level variables, including indicators for air basin and census tract-based urban/rural status, modeled nitrogen dioxide (NO_2) concentrations, and a measure of income concentration. These covariates accounted for neighborhood and regional differences in air quality, economic activity, and emission sources (Arruti et al. 2011; Finkelstein et al. 2003; O'Neill et al. 2003; Wunderli and Gehrig 1990; Zhao et al. 2009). We used 2014 air basin boundaries designated by the California Air Resources Board (CARB 2014), which coincide with county boundaries and roughly delineate areas with similar air quality, meteorology, and geography. We used U.S. Census urban areas [defined as a densely developed territory consisting of urbanized areas of 50,000 or more and urbanized clusters with between 2,500 and 50,000 people (U.S. Census Bureau 2010)] to designate census tracts as urban or rural. Using 2010 boundaries, we categorized census tracts as urban if 60% or more of the tract overlapped with an urban area. We assigned, based on LMP year, tract-level annual ambient NO_2 concentration as a proxy for traffic-related air pollution (Kim et al. 2018). Last, we used the Index of Concentration at the Extremes (ICE) for income as a measure of neighborhood relative deprivation or affluence based on household income by census tract (Massey 1996). ICE provides information about concentration of privilege and deprivation of communities and has previously been associated with infant mortality (Krieger et al. 2016). ICE ranges from -1 to 1, where negative values indicate a concentration of household incomes in the lower 20th percentile of area median household income, whereas positive values indicate a concentration of household incomes in the higher 80th percentile. We calculated ICE using 2006–2010 ACS and 2011–2015 ACS metropolitan area median household income to establish percentile cutoff values that account for regional differences in the cost of living. These values were then used in combination with census tract median household income from the ACS data of the vintage of the birth year to assign a tract-level ICE value to each birth. For tracts that were not within metropolitan areas, county-level household income cutoffs were used. ICE was categorized by quartile and this categorical variable was included in adjusted models.

Statistical Analyses

Statistical analyses were conducted in SAS 9.4 (SAS Institute Inc.). All models were adjusted for individual-level and community-level covariates selected *a priori*: neonate sex, gestational age (tBW model only), month and year of birth, maternal age, race/ethnicity, educational attainment, Kotelchuck index, urban indicator, air basin, NO_2, and ICE for income. Generalized estimating equations were used to account for clustering of mothers within census tracts (Hubbard et al. 2010). Observations with any missing covariate were removed from analyses.

Initial analyses assessed exposure across the entire pregnancy and then during each trimester for the entire study population across the four air basins. Statistical significance was assessed at $\alpha = 0.05$. Effect modification (EM) of exposure to active wells by urban/rural status (primary), maternal race/ethnicity, and air basin (both secondary) was evaluated via stratification. We report the strata-specific effect estimates and confidence intervals derived from this methodology. To test the heterogeneity between strata-specific estimates, we modeled interaction terms to derive Bonferroni adjusted p-values for two-sample z-tests using model-estimated beta coefficients and variances (Buckley et al. 2017; UCLA: Statistical Consulting Group). These EM p-values indicate whether the strata-specific associations are statistically significantly different from each other or the referent group. Non-Hispanic whites were used as the referent in heterogeneity tests for the other racial/ethnic groups because higher rates of adverse birth outcomes have been observed among people of color in

Table 1. Neonate, maternal, and area-level characteristics of births by oil and gas well production volume category, California 2006–2015. Prepregnancy BMI and smoking during pregnancy were available for 2007–2015 births (2006 births excluded from the missing category).

Variable	*n* (%)	No BOE (*n* = 2,866,735)	Production volume 1–100 BOE/day (*n* = 70,615)	GT 100 BOE/day (*n* = 50,079)	*p*-Value[a]
Neonate characteristics					
Mean birth weight [g (mean ± SD)]	2,987,429 (100)	3,327 ± 528	3,318 ± 527	3,316 ± 527	<0.0001
Mean gestational age [weeks (mean ± SD)]	2,987,429 (100)	39 ± 2	39 ± 2	39 ± 2	<0.0001
Sex					
Female	1,456,548 (49)	49	48	49	0.2879
Male	1,530,866 (51)	51	52	51	—
Missing[b]	15 (<1)	100	0	0	—
Birth month					
January	244,433 (8)	8	8	8	0.3261
February	224,691 (8)	8	8	8	—
March	245,683 (8)	8	8	8	—
April	233,297 (8)	8	8	8	—
May	242,652 (8)	8	8	8	—
June	241,962 (8)	8	8	8	—
July	260,028 (9)	9	9	9	—
August	269,714 (9)	9	9	9	—
September	266,586 (9)	9	9	9	—
October	261,399 (9)	9	9	9	—
November	245,566 (8)	8	8	8	—
December	251,418 (8)	8	8	8	—
Birth year					
2006	320,330 (11)	11	10	12	<0.0001
2007	320,698 (11)	11	11	12	—
2008	312,732 (10)	10	10	11	—
2009	300,201 (10)	10	10	10	—
2010	290,469 (10)	10	10	10	—
2011	288,006 (10)	9	10	9	—
2012	288,855 (9)	10	10	9	—
2013	287,425 (10)	10	10	9	—
2014	293,637 (10)	10	10	9	—
2015	285,076 (10)	9	9	9	—
Maternal Characteristics (%)					
Education					
<High school	764,090 (26)	26	31	21	<0.0001
High school diploma/GED	764,206 (26)	26	23	21	—
Some college	724,574 (25)	25	22	23	—
College+	665,993 (23)	23	24	35	—
Missing[b]	68,566 (2)	95	3	2	—
Age at delivery					
<20	252,857 (8)	9	9	6	<0.0001
20–24	651,062 (22)	22	21	18	—
25–29	809,072 (27)	27	27	25	—
30–34	754,714 (25)	25	26	29	—
35+	519,700 (17)	17	17	22	—
Missing[b]	24 (<1)	92	8	0	—
Race/ethnicity					
Asian/Pacific Islander	356,603 (12)	12	11	13	<0.0001
Black	154,047 (5)	5	6	9	—
Hispanic	1,673,517 (56)	56	59	47	—
Other	84,384 (3)	3	2	4	—
White	718,878 (24)	24	22	27	—
Kotelchuck index					
Inadequate	351,729 (12)	12	13	12	<0.0001
Intermediate	349,946 (12)	12	12	9	—
Adequate+	905,545 (30)	30	29	34	—
Adequate	1,380,209 (46)	46	46	45	—
Parity					<0.0001
Nulliparous	1,154,875 (39)	39	40	44	—
Multiparous	1,831,556 (61)	61	60	56	—
Missing[b]	998 (<1)	93	4	3	—
Mean pre-pregnancy BMI[c] (SD)	2,472,066 (93)	26 ± 6	26 ± 6	25 ± 6	<0.0001
Missing[b]	195,033 (7)	94	4	2	—
Smoking during pregnancy[c]					<0.0001
Smoked	49,461 (2)	2	1	1	—
Did not smoke	257,7903 (97)	98	99	99	—
Missing[b]	39,735 (1)	92	5	3	—
TRI facility: 1+within 1 km	48,189 (2)	2	4	3	<0.0001

Table 1. *(Continued.)*

Variable	n (%)	No BOE ($n=2{,}866{,}735$)	Production volume 1–100 BOE/day ($n=70{,}615$)	GT 100 BOE/day ($n=50{,}079$)	p-Value[a]
Area-level characteristics (%)					
Mean NO_2 [ppb (mean ± SD)]	2,987,408 (99)	16 ± 7	18 ± 7	19 ± 5	<0.0001
Missing[b]	21 (<1)	95	0	5	—
Urban	2,651,066 (89)	89	87	97	—
Air Basin					
Sacramento Valley	296,668 (10)	10	1	0.5	<0.0001
San Joaquin Valley	563,276 (19)	19	21	4	—
South Central Coast	178,647 (6)	6	6	1	—
South Coast	1,948,838 (65)	65	72	94	—
ICE					
Quartile 1–poverty	731,431 (25)	25	31	27	<0.0001
Quartile 2	731,403 (25)	25	23	19	—
Quartile 3	730,283 (25)	25	19	23	—
Quartile 4–wealth	724,972 (25)	25	27	31	—
Missing[b]	217 (<1)	76	9	15	—
Oil/gas wells					
Mean inactive well count (mean ± SD)	2,987,429 (100)	0	89 ± 111	160 ± 191	<0.0001
Mean active well count	2,987,429 (100)	0	4 ± 4	32 ± 27	<0.0001
Mean production volume (BOE)/d (mean ± SD)	2,987,429 (100)	0	26 ± 26	599 ± 711	<0.0001

Note: —, No data; BOE, barrels of oil equivalent; ICE, Index of Concentration at the Extremes.
[a]ANOVA or chi-square test.
[b]Distribution of missingness across categories of production volume rather than percent missing in each production volume category.
[c]No covariate data available for 2006 (not included as missing), $n=2{,}667{,}099$ births between 2007 and 2015.

comparison with whites (Bryant et al. 2010; Teitler et al. 2007). Sacramento Valley was the referent in heterogeneity tests for the other air basins because exposures to active wells were limited to rural areas of that basin, where there were also fewer births. For the effect modification analyses with race/ethnicity and air basin, only exposure across the entire pregnancy was evaluated because trimester-specific estimates were similar to those for the entire pregnancy.

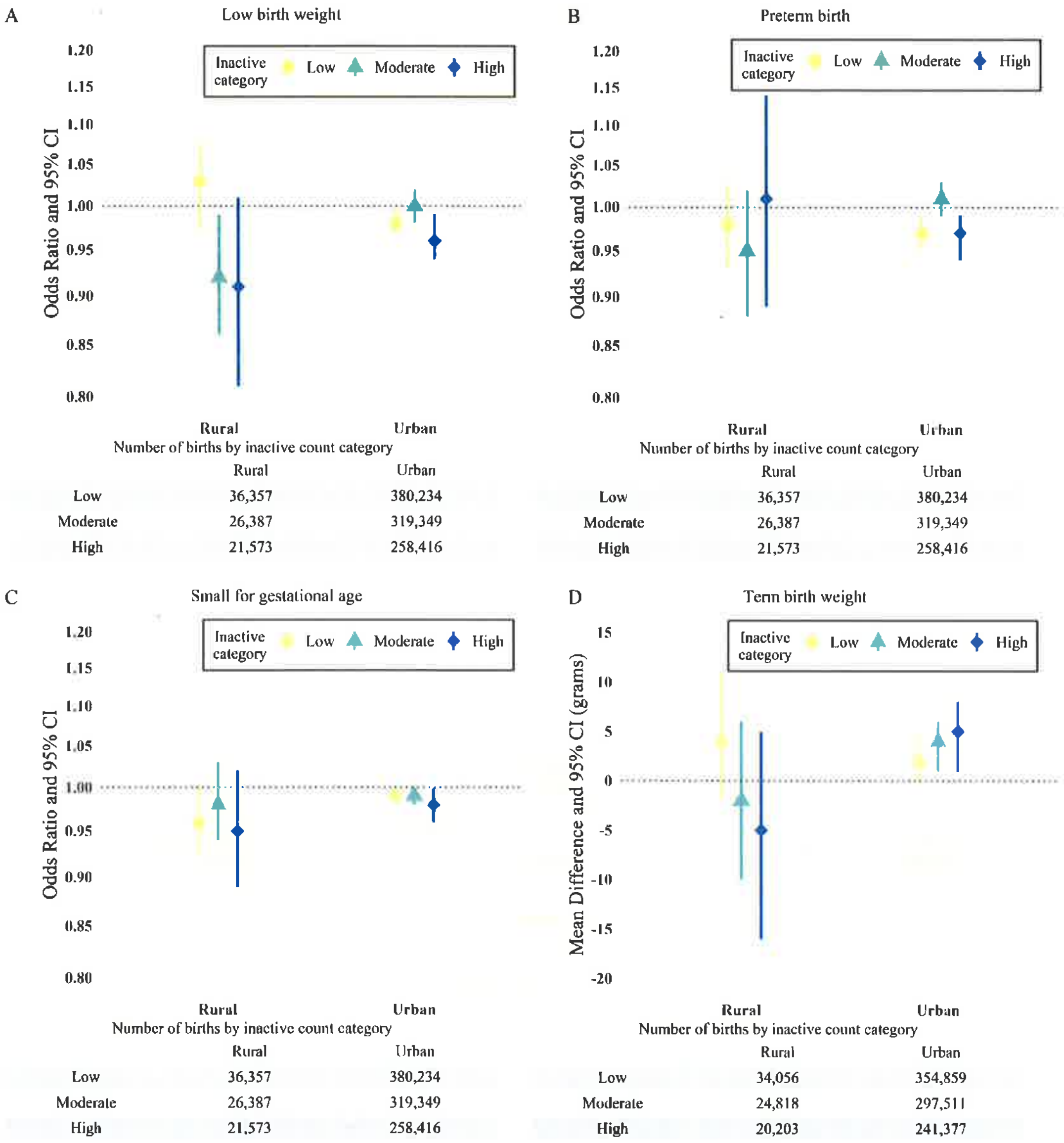
We conducted two sensitivity analyses with exposure variables across the entire pregnancy only. Mothers' smoking status during pregnancy and prepregnancy body mass index (BMI) were not collected by CDPH in 2006, so we conducted sensitivity analyses with both of these variables in one model for 2007–2015. Only 2% of mothers smoked during pregnancy among our study population within our study period (prevalence of smoking during pregnancy in CA was 2.5% in 2015) (CDPH 2015). Additionally, we considered potential confounding from other industrial sources of air pollution and included a binary variable for exposure to air pollution from other facilities (e.g., refineries, power plants, metal mining facilities) monitored for emissions, including air toxics by the CARB (CARB 2017) within 1 km (referred to as TRI facilities). Only ~2% of mothers resided within proximity to TRI facilities during our study period.

We tested for multicollinearity between all model variables by calculating the variance inflation factors (Schreiber-Gregory 2012), none of which were high (i.e., >10). To assess residual spatial dependence, we generated semivariograms of regression residuals plotted against distance between mothers' residential addresses (Le Rest et al. 2013; SAS) (Figure S3). The residuals appeared randomly distributed, suggesting spatial autocorrelation was likely controlled for by the study design and inclusion of spatial covariates (e.g., NO_2) in regression models.

Results

Our study included 2,918,089 births in CA between January 2006 and December 2015 located in four air basins: the Sacramento Valley, San Joaquin Valley, South Central Coast, and South Coast. The overall mean birth weight was 3,327 g [standard deviation (SD) = 528] (Table 1). Five percent ($n=148{,}100$) of births were LBW, 7% ($n=199{,}460$) preterm, and 12% SGA ($n=337{,}943$). A maximum of 1,189 inactive wells and 441 active wells were located within 1 km of mothers' residences during pregnancy. On average, mothers exposed to moderate production volume (1–100 BOE/d) had 89 inactive and 4 active wells within 1 km of their home during pregnancy, whereas mothers exposed to high production volume (>100 BOE/d) had an average of 160 inactive wells and 32 active wells within a 1-km buffer. The average moderate total production volume from active wells producing oil and gas during pregnancy was 26 BOE/d, and the average high total production volume was 599 BOE/d. Temporal trends of mean annual production volume and annual rates of the binary birth outcomes showed no distinct patterns in either rural or urban areas (Figure S4A,B). Plots of temporal trends in mean annual production volume and mean annual tBW also did not reveal consistent patterns in either rural or urban areas (Figure S4C,D). The reference (no BOE) and exposed populations were relatively similar in terms of demographic and socioeconomic factors (Table 1). Compared to the reference and moderate production volume groups, mothers in the high production volume category were slightly more educated (35% vs. 23.5%, on average, college or more educated), older (22% vs. 17%, on average, aged 35 or more), more often non-Hispanic (53% vs. 42.5%, on average, non-Hispanic races), more likely to have no previous pregnancies (44% vs. 39.5%, on average, nulliparous), and to reside in urban areas (97% vs. 88%, on average), in the South Coast air basin (94% vs. 68.5%, on average) and in areas with greater wealth (31% vs. 26%, on average, in ICE quartile 4). Finally, babies born to mothers exposed to high production volume weighed on average 2 and 11 grams less than those born to mothers exposed to moderate production volume and reference group, respectively.

Adjusted models generally found no associations between inactive well count and adverse birth outcomes in both rural and urban areas (Figure 3, Tables S1–S2). All statistically significant associations indicated modestly decreased odds of LBW and PTB (0.96–0.97) (Figure 3A,B; Table S1) or minimally increased birth weight (4–5 g) (Figure 3D; Table S2) related to increased inactive OGD well exposure. Models based on trimester-specific exposures yielded similar estimates across trimesters for all four birth outcomes (Table S1–S2).



Number of births by inactive count category (A)

	Rural	Urban
Low	36,357	380,234
Moderate	26,387	319,349
High	21,573	258,416

Number of births by inactive count category (B)

	Rural	Urban
Low	36,357	380,234
Moderate	26,387	319,349
High	21,573	258,416

Number of births by inactive count category (C)

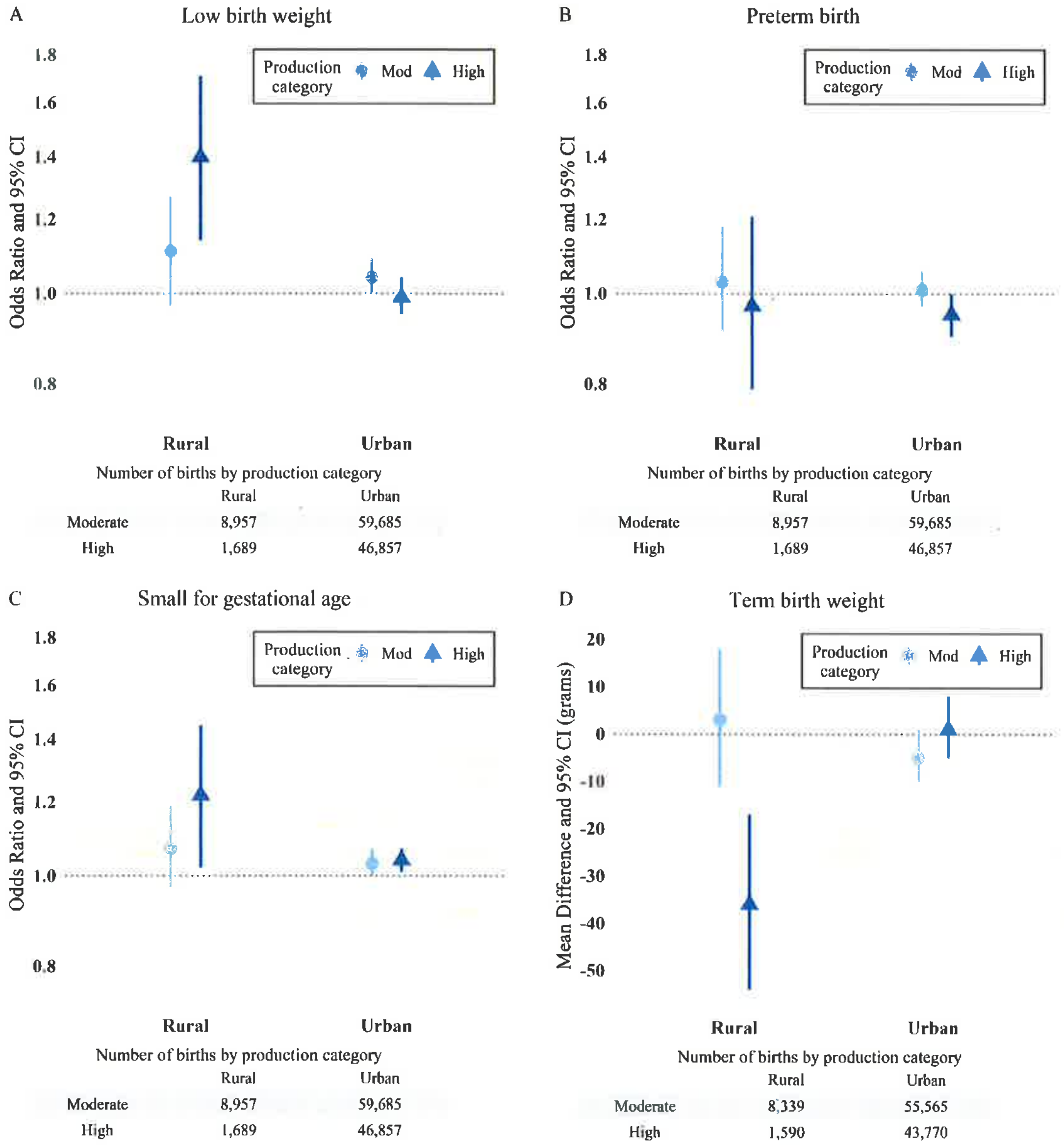
	Rural	Urban
Low	36,357	380,234
Moderate	26,387	319,349
High	21,573	258,416

Number of births by inactive count category (D)

	Rural	Urban
Low	34,056	354,859
Moderate	24,818	297,511
High	20,203	241,377

Figure 3. Plots of rural vs. urban odds ratios or mean difference in birth weight (grams) and 95% confidence interval (CI) for associations between exposure to low, moderate, and high counts of inactive wells across the entire pregnancy and low birth weight (A), preterm birth (B), small for gestational age (C), and continuous term birth weight (D). Logistic regression models adjust for inactive well count, child's sex, birth month and birth year, and maternal education, age, race/ethnicity, Kotelchuck prenatal care index, parity, air basin, NO_2 and ICE for income. In addition to the covariates adjusted for in the logistic regression models, the linear regression models also adjusted for gestational age. All *y*-axes are on the logarithmic scale except for on the term birth weight plot. Numerical values plotted here can be found along with estimates for the three trimesters and *p*-values for statistical tests for effect modification in Tables S1–S2.

For exposures to production volume from active wells in unstratified models, we observed significant associations between production volume and LBW and SGA (Table S3). When we stratified models by the urban indicator, we observed significant effect modification with stronger associations between high production volume and LBW ($p = 0.01$, Table S4) and tBW ($p = 0.001$, Table S7) in rural areas (Figure 4). Compared to the reference group, the odds ratio for LBW was 1.11 [95% confidence interval (CI): 0.97, 1.27] (Table S4) and the OR for SGA was 1.07 (95% CI: 0.97, 1.19) (Table S6) with exposure to moderate production volume across the entire pregnancy in rural areas vs. ORs of 1.04 (95% CI: 1.00, 1.09) and 1.03 (95% CI: 1.00, 1.07), respectively, in urban areas (Figure 4A,C). Exposure to high production volume was associated with an OR of 1.40 (95% CI: 1.14, 1.71) for LBW and an OR of 1.22 (95% CI: 1.02, 1.45) for SGA in rural areas vs. ORs of 0.99 (95% CI: 0.95, 1.04) and 1.04 (95% CI: 1.01, 1.07), respectively, in urban areas (Figure 4A,C; Tables S4, S6). Exposure to high production volume was also associated with decreased tBW (mean difference = −36 g; 95% CI: −54, −17) for the rural stratum in comparison with the urban stratum (mean difference = 1 g, 95% CI: −5, 8) (Figure 4D; Table S7). For LBW, SGA, and tBW, the strength of the associations increased with higher production volume among the rural, but not the urban, population. In general, exposure to production volume throughout pregnancy was not associated with PTB within rural or urban populations (Figure 4B; Table S5). Models based on trimester-specific exposures yielded similar estimates and EM *p*-values for all birth outcomes (Tables S4–S7), except the third trimester for PTB, where exposure to moderate production volume was associated with increased odds of PTB (OR = 1.06; 95% CI: 1.02, 1.11) and high production volume was associated



A

Number of births by production category

	Rural	Urban
Moderate	8,957	59,685
High	1,689	46,857

B

Number of births by production category

	Rural	Urban
Moderate	8,957	59,685
High	1,689	46,857

C

Number of births by production category

	Rural	Urban
Moderate	8,957	59,685
High	1,689	46,857

D

Number of births by production category

	Rural	Urban
Moderate	8,339	55,565
High	1,590	43,770

Figure 4. Plots of rural vs. urban odds ratios or mean difference in birth weight (grams) and 95% confidence interval (CI) for associations between exposure to moderate and high production volume across the entire pregnancy and low birth weight (A), preterm birth (B), small for gestational age (C), and continuous term birth weight (D). Logistic regression models adjust for inactive well count, child's sex, birth month and birth year, and maternal education, age, race/ethnicity, Kotelchuck prenatal care index, parity, air basin, NO_2 and ICE for income. In addition to the covariates adjusted for in the logistic regression models, the linear regression models also adjusted for gestational age. All *y*-axes are on the logarithmic scale except for on the term birth weight plot. Numerical values plotted here can be found along with estimates for the three trimesters and *p*-values for statistical tests for effect modification in Tables S4–S7.

with decreased odds of PTB in urban areas (OR = 0.82; 95% CI: 0.77, 0.88) (Table S5).

Maternal race/ethnicity (Tables S8–S9) and air basin (Tables S10–S11) did not significantly modify associations between exposure to active well production volume and birth outcomes. Heterogeneity tests were only conducted on the rural population because the effect sizes across outcomes were greater than those of the urban population. Nearly all strata-specific effect estimates included the null and all EM *p*-values from heterogeneity tests were insignificant across all outcomes.

Sensitivity analyses that included: *a*) prepregnancy BMI and smoking during pregnancy for 2007–2015 births (Table S12) and *b*) exposure to TRI facilities (Table S13) did not change effect estimates by more than 10%.

Discussion

CA's OGD primarily uses conventional drilling and enhancement methods and, to a much lesser degree, HF. To our knowledge, our study is the first to quantify prenatal exposures to both inactive wells and cumulative oil and gas production volume from active wells in proximity to pregnant women and to evaluate differences in associations by rural vs. urban areas in CA. In rural areas, we found that exposure to high production volume was significantly associated with increased odds of LBW and SGA and decreased tBW in comparison with the nonexposed group. In urban areas, exposure within 1 km of high production volume relative to no exposure was only significantly associated with increased odds of SGA; effect estimates for exposure to moderate production volume in rural and urban areas were all insignificant.

One prior study, by McKenzie et al. (2019), evaluated urban/rural residential status as an effect modifier. Although that study examined birth defects, the authors found significantly increased odds for four congenital heart defects in the medium and highest exposure groups (based on an intensity-adjusted inverse-distance weighted well-count metric) relative to the lowest group in rural areas (McKenzie et al. 2019); no significant associations were observed for birth defects in urban areas. These rural vs. urban differences in effect estimates align with the stronger effect estimates we observed in rural areas in CA for LBW and tBW. McKenzie et al. (2019) also discovered a potential additive effect from other sources of air pollution besides OGD in their analysis. Here, we considered residual confounding from TRI facilities within 1 km, but inclusion of this covariate did not change the rural/urban strata-specific effect estimates. Nevertheless, there may be residual confounding from other sources of air or drinking water pollution that we could not account for in our analysis. For example, the ratio of produced water from OGD (which can contain naturally occurring or injected organic/inorganic chemicals, chemicals that are reaction byproducts, and radioactive materials) to oil and gas extracted increases with well age (Veil et al. 2004). Certain chemicals from produced water could evaporate into the air or percolate into groundwater sources, depending on disposal methods (Long et al. 2015a). Air and water pollution concentrations could differ regionally based on dispersion and hydrological transport patterns. Additionally, individual factors that we could not measure in our study, such as maternal occupation, housing quality, indoor air quality, dependence on groundwater sources for drinking water, and underlying population sensitivity to OGD-related pollutants may have contributed to observed differences in effect estimates between rural and urban settings. In the air pollution literature, the exposure–response relationship between cardiovascular disease mortality and $PM_{2.5}$ is relatively steep at low levels of exposure but flattens out at higher levels (Pope et al. 2009; Smith and Peel 2010). Such exposure–response relationships could apply to the OGD setting where urban dwellers may be less affected by OGD-specific pollutants because OGD as an emission source contributes a relatively small percentage to ambient air pollution levels in urban areas, which tend have higher pollutant concentrations overall from diverse mobile and stationary sources. Indeed, average NO_2 levels among urban areas in our study were double that of rural areas.

Results from our analysis align with prior studies that observed decreased birth weight associated with maternal exposure to OGD activities (Currie et al. 2017; Hill 2018; Stacy et al. 2015). However, associations between exposure to OGD and LBW and SGA from other studies have been mixed, with increased odds (Stacy et al. 2015) or incidence probability (Currie et al. 2017; Hill 2018) as well as decreased odds (McKenzie et al. 2014) or no associations (Casey et al. 2015; Whitworth et al. 2017). Although the mechanisms by which OGD may adversely affect birth weight outcomes remain uncertain, air pollution and noise may be possible pathways that affect maternal health during pregnancy. During production, operation of various ancillary equipment (e.g., wellhead compressors, pneumatic devices, separators, and dehydrators) to collect and process oil and gas generate air pollutants (Garcia-Gonzales et al. 2019). Multiple VOCs have been measured at oil and gas wellheads and off-site, including BTEX and formaldehyde. At ambient levels, BTEX and formaldehyde have been linked to significant decreases in birth weight (Bolden et al. 2015; Chang et al. 2017; Maroziene and Grazuleviciene 2002). Flaring also occurs with oil-producing and horizontally drilled wells (Franklin et al. 2019) and can contribute to spikes in $PM_{2.5}$, black carbon, and VOCs during production (Allshouse et al. 2019; Franklin et al. 2019). Relative to other phases of OGD, excessive noise is minimized during production (Allshouse et al. 2019; Hays et al. 2017). However, noise from compressor stations often exceed the World Health Organization's recommended 55 dBA at night (Hays et al. 2017) and noise above 65 dBA was measured 20% of the time between 1900 hours and 0700 hours (7:00 P.M. and 7:00 A.M.) in one study (Allshouse et al. 2019). Excessive noise can lead to annoyance and impaired sleep quality (Hays et al. 2017), which have been linked to LBW (Abeysena et al. 2010; Owusu et al. 2013) and PTB (Li et al. 2017).

Unlike previous studies, we found no significant association between exposure to active wells and PTB except in the third trimester in urban areas where moderate exposure appeared harmful and high exposure protective. Exposure to OGD was associated with modestly decreased odds for PTB (Stacy et al. 2015) and increased odds (Casey et al. 2015) in Pennsylvania and increased odds in Texas (Walker Whitworth et al. 2018; Whitworth et al. 2017). The two Pennsylvania studies were conducted in different regions of Pennsylvania and among different populations [general for Stacy et al. (2015) and patients served by one health-care provider for Casey et al. (2015)]. The inverse association in the Stacy et al. (2015) analysis was only observed for the second quartile of exposure in comparison with the lowest quartile, whereas the association increased with greater exposure (quartiled) in the Casey et al. (2015) study. In Texas, the association was only significant with the highest level of exposure within 10 miles (Walker Whitworth et al. 2018) and the first and second trimesters with exposure within half a mile (Whitworth et al. 2017). Associations for PTB appear to vary by level of exposure as well as trimester. We only observed significant associations—increased odds with moderate exposure and decreased odds with high exposure—in urban areas in the third trimester. Previous studies on air pollution and birth outcomes have suggested that the first and third trimesters are critical windows of exposure for LBW and PTB (Ritz and Wilhelm 2008; Woodruff et al. 2009). Additionally, the significant inverse association between high OGD exposure and PTB in urban areas may reflect residual confounding or live-birth bias. Other socioeconomic status characteristics that were not controlled for in our models could have led to underlying differences among urban dwellers or their exposure patterns. Moreover, if more highly exposed or more vulnerable mothers were less likely to become pregnant or more likely to experience fetal loss, a so-called "depletion of susceptibles" could have occurred (Raz et al. 2018), and a seemingly protective effect would then be observed. Although we could not evaluate fertility patterns or spontaneous abortion in our analysis, a study in Ecuador observed greater odds of spontaneous abortion among women who lived within 5 km downstream of an oil field in comparison with those who lived at least 30 km upstream of an oil field (San Sebastian et al. 2002).

The inconsistent results across studies may reflect differences in statistical and exposure assessment methods, study population demographics, and OGD infrastructure. First, to limit unmeasured confounding, our analyses restricted the study population to those individuals living within 10 km of at least one active or inactive well at the time of delivery. Similar to Whitworth et al. (2017), we specified the unexposed group as those pregnancies with some well activity, but no well activity within 1 km. Besides their exposure, the control and exposed groups are likely more similar to each other on other characteristics (e.g., unmeasured socioeconomic factors) than a control group selected from greater distances or other regions. Second, we applied a 1-km buffer for our exposure metric without weighting, i.e., without up-weighting wells at a shorter distance from maternal residences. Previous studies used inverse distance weighting (McKenzie et al. 2014; Stacy et al. 2015) or inverse distance squared weighting (Casey et al. 2015; Walker Whitworth et al. 2018, 2017) but often included wells beyond our 1-km buffer.

Inverse distance weighting has been applied in many air pollution studies (de Mesnard 2013). Although air pollution may be a large contributor to OGD-related exposure, we did not assume that it is the only OGD-related hazard, and within such a short distance (1 km), dispersion patterns of OGD pollutants may be relatively uniform. Therefore, we weighted all wells equally within the 1-km buffer. Third, we examined separate effects of inactive wells and active well production volume, whereas prior studies have not considered inactive wells separately and often only examined the density of (McKenzie et al. 2014; Stacy et al. 2015; Whitworth et al. 2017) or total production volume from unconventional wells (Casey et al. 2015; Walker Whitworth et al. 2018). Including both inactive and active wells allowed us to distinguish possible differential effects by well type. Fourth, our CA study population was more racially and ethnically diverse than those in other studies conducted in Colorado and Pennsylvania, which may contribute to differences in analytical results. Finally, California's OGD infrastructure is older than infrastructure in other states and utilizes less HF in comparison with OGD in Pennsylvania, Colorado, and other states where production infrastructure is newly established (Long et al. 2015b). These regional differences in OGD infrastructure may affect the type of hazards associated with them and their implications for maternal health and birth outcomes.

Our study is the first to highlight differences in potential health impacts of exposure to active OGD based on total production volume from both oil and gas wells and inactive wells. We did not, however, directly measure OGD environmental impacts via, for example, air or drinking water monitoring near active or inactive wells. Several OGD-related hazards—air toxics, water pollutants, noise, excessive lighting—may elicit a variety of biological responses, but our exposure measure precluded identification of specific pathways through which OGD may affect birth outcomes. Further, the cumulative exposure–response curve of all of the potential hazards and health outcomes may differ than that for each individual hazard separately. For example, living in proximity to oil and gas fields and seeing the active rigs daily might induce stress, worry, and lack of sleep (Ferrar et al. 2013; Hirsch et al. 2018; Long et al. 2015a; Palagini et al. 2014). However, individuals may habituate, leading to biological responses that may peak and level off (Basner et al. 2011), whereas we might expect a linear exposure–response related to air pollution exposures.

We observed some modest inverse associations between inactive wells and birth outcomes, primarily in urban areas. Inactive wells can pose risks in several ways. To date, excessive fugitive methane emissions have been measured at abandoned (unplugged) well sites, with higher concentrations detected at sites with compromised wells (Boothroyd et al. 2016; Kang et al. 2016). Residual off-gassing of air contaminants such as BTEX could also occur, which has prompted the South Coast air district and DOGGR to begin to collect air toxics and VOCs emissions data (LACDPH 2018; SCAQMD 2019; California AB1328). Of greater concern is contamination of potable water sources from subsurface leakage and migration of contaminants through abandoned or idle wells (Long et al. 2015a). In an assessment of groundwater contamination from OGD in Ohio and Texas over more than a decade, abandoned wells accounted for 22% (Ohio) and 14% (Texas) of contamination incidents (Ground Water Protection Council 2011). In CA, idle wells may be repurposed for wastewater disposal or later revitalized with new technologies (Walker 2011). Wells operating with old infrastructure pose greater risks of leakages through the well casing and cement barriers (Ingraffea et al. 2014). HF could also increase the risk of surface or groundwater contamination via abandoned wells due to hydrological pressure changes; in one rare incident, an abandoned well in Pennsylvania produced a 30-foot geyser of brine and gas for more than a week after a nearby gas well underwent HF (EPA 2016). We may not have observed any consistent or significant associations between exposure to inactive wells and adverse birth outcomes because we were not able to capture these nuanced exposure pathways with well count alone, leading to potential exposure misclassification.

Other limitations include our inability to adjust for several individual-level factors. Due to lack of data linkage, we could not control for the correlation between siblings (though we do include parity in all models) or maternal mobility during pregnancy. Birth records did not include a linking variable for siblings and only documented the residential address at time of birth. Previous studies on impacts of residential mobility during pregnancy suggest that ignoring residential mobility may lead to modest bias in associations toward the null or result in nondifferential exposure misclassification (Chen et al. 2010; Hodgson et al. 2015; Lupo et al. 2010; Pennington et al. 2017). However, exposure estimates based on addresses captured at birth vs. conception have been highly correlated (Chen et al. 2010; Lupo et al. 2010; Pennington et al. 2017). Across studies, $\leq 30\%$ of mothers moved during pregnancy and moving distances were relatively short and within the same county (Bell and Belanger 2012; Chen et al. 2010; Hodgson et al. 2015; Lupo et al. 2010; Miller et al. 2010; Pennington et al. 2017). The extent of misclassification error depends on the spatial variability in the exposure (Hodgson et al. 2015). Additionally, exposure misclassification may be less prominent in the third trimester. Across environmental epidemiological studies that evaluated the impact of residential mobility on effect estimates by trimester, the highest rates of mobility occurred in the second trimester (Bell et al. 2018; Bell and Belanger 2012). Lowest residential mobility was observed in the first trimester among three studies and in the third trimester among two studies (Bell et al. 2018; Bell and Belanger 2012). Exposure misclassification due to mobility in the third trimester is less likely to be an issue, due to its proximity to the time of delivery, when the maternal residential address is collected and listed on the birth certificate. In addition to residential mobility, maternal occupational mobility should also be considered. One study that evaluated the impact of occupational mobility on air pollution exposure misclassification among Parisian women in the two first trimesters found that mode of transport increased NO_2 exposure in the first trimester (Blanchard et al. 2018). Our study results yielded similar effect estimates across trimesters, suggesting that any bias resulting from maternal residential and occupational mobility is likely nondifferential across trimesters.

In summary, this study expands the current literature on the health implications of OGD. We observed that prenatal exposure to active oil/gas production from both conventional and unconventional wells in CA was associated with adverse birth outcomes, and these associations varied by rural and urban areas. We observed the strongest associations with exposure to high production volume in rural areas. Future studies should consider inactive wells and conduct exposure assessments that collect environmental samples of OGD-related hazards. Such data would greatly improve exposure assignment and advance our understanding of underlying exposure sources and pathways. Additional evaluations of the relationship between oil/gas operator size, pollutant emissions, and frequency and type of violations and health outcomes would also elucidate which types of wells may be of greatest concern. Such data can inform regulatory decisions in terms of prioritizing inspection and pollution monitoring as well as emissions reduction requirements and community exposure reduction strategies.

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ANNUAL REVIEWS

Annual Review of Public Health

Hazardous Air Pollutants Associated with Upstream Oil and Natural Gas Development: A Critical Synthesis of Current Peer-Reviewed Literature

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Keywords

hazardous air pollutants, volatile organic compounds, oil and natural gas, air quality, oil and gas development

Abstract

Increased energy demands and innovations in upstream oil and natural gas (ONG) extraction technologies have enabled the United States to become one of the world's leading producers of petroleum and natural gas hydrocarbons. The US Environmental Protection Agency (EPA) lists 187 hazardous air pollutants (HAPs) that are known or suspected to cause cancer or other serious health effects. Several of these HAPs have been measured at elevated concentrations around ONG sites, but most have not been studied in the context of upstream development. In this review, we analyzed recent global peer-reviewed articles that investigated HAPs near

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Ex. 30

ONG operations to (*a*) identify HAPs associated with upstream ONG development, (*b*) identify their specific sources in upstream processes, and (*c*) examine the potential for adverse health outcomes from HAPs emitted during these phases of hydrocarbon development.

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1. INTRODUCTION

Over the past several decades, as energy demands have increased contemporaneously with innovations in upstream oil and natural gas (ONG) extraction technologies, the United States has become the world's top producer of petroleum and natural gas hydrocarbons (34). The US Energy Information Administration (104) reported that US petroleum and other liquid fuel production reached 9.3 million barrels per day, and dry natural gas production averaged 73.6 billion cubic feet per day in 2017, with increases projected for 2018 and 2019. In some areas, including Pennsylvania, Colorado, Texas, and California, ONG extraction and development have expanded closer to residential communities, increasing risks of population exposures to air, water, soil, noise, and light pollution. Research suggests that current setback standards—or distances in which the ONG industry can develop from water sources, residential structures, and other facilities—may not be sufficient to reduce potential risks to human health from ONG activities (12, 53). A growing, yet still relatively small body of studies has investigated the relationship between the proximity of these facilities and human health impacts (21, 22, 31, 60, 78, 79, 96, 97, 99). With a dearth of scientific data characterizing exposure risks, it is difficult to offer scientific guidance on specific adequate setback requirements, despite the fact that an estimated 18 million people live within 1,600 m (~1 mile) from an active ONG well (32). Special disclosure exemptions from the federal Emergency Planning and Community Right-to-Know Act allow the ONG industry to withhold information regarding chemical constituents used, produced, and emitted, further compounding the difficulty in identifying chemical-related hazards and their associated exposure pathways (106).

The current body of scientific literature suggests that upstream ONG development processes emit numerous air pollutants, including methane, nonmethane-volatile organic compounds (VOCs), particulate matter (PM), aliphatic and aromatic hydrocarbons, aldehydes, and nitrogen oxides, some of which are also precursors to tropospheric ozone and secondary organic aerosol (SOA) production (18, 41, 89, 95, 111, 115, 122). Upstream ONG development includes all phases and processes necessary to extract ONG hydrocarbons from subsurface reservoirs, excluding the transportation, transmission, storage, refinement, and wholesale of refined products. Upstream processes consist of four broad phases of operation: (*a*) exploration and well pad and infrastructure construction; (*b*) well drilling and construction of associated surface and subsurface equipment and facilities; (*c*) application of well stimulation or secondary oil and gas recovery techniques (e.g., water flooding and steam injection) and completion, or both; and (*d*) hydrocarbon production and processing. Various attempts to identify and classify all products and chemicals used or emitted during the upstream ONG development process have resulted in disparate lists ranging from 343 to 1,177 unique chemicals, some classified as HAP compounds with known carcinogenic and noncarcinogenic toxicological properties (26, 38, 82, 108). Current research on oil and gas development provides conflicting evidence over the concentrations of various pollutants in the air across geographic, regulatory, and corporate spaces; however, a consensus exists regarding the presence of air pollutants that can pose human health hazards around ONG sites (19, 27, 48, 56, 68, 73, 79, 88).

Emissions of hazardous air pollutants (HAPs) from ONG are of particular concern because they are known or suspected to cause cancer or other serious noncancer health effects. The US Clean Air Act currently lists 187 HAPs for regulation (107), some of which have been associated with ONG activities. The Committee on Energy and Commerce and the Endocrine Disruption Exchange have identified more than 20 different HAPs, which have been associated with upstream ONG activities or processes (101, 109). While the number of studies examining the human health impacts of ONG development is growing, limited information exists on the role of HAPs in the upstream process and the health impacts of HAP-related emissions (18, 44, 80, 114).

The purpose of this review is to summarize the research conducted to date on the associations between HAPs and upstream ONG development. Specifically, this article aims to (*a*) identify HAP compounds that have been investigated near upstream operations within the peer-reviewed literature; (*b*) determine which of these compounds has been traced to a specific upstream phase, process, or source; and (*c*) examine the potential health hazards attributable to these HAPs. Our synthesis of the science is intended to inform future research priorities and to assist in public health protection. A list of ONG industry terms can be found in the sidebar titled Terms and Definitions.

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TERMS AND DEFINITIONS

Anthropogenic: originating from human activities. With air pollution, these activities include those related to transportation (or mobile), agriculture, or industry sources.

BTEX: the group of compounds, including benzene, toluene, ethylbenzene, and total xylenes. These compounds occur naturally in petroleum and are released primarily through motor vehicle emissions, but they are also emitted naturally via volcanoes and forest fires.

Condensate: broadly defined as a liquid formed by condensation. With oil and natural gas, condensate is a gas that condenses into a liquid hydrocarbon mixture after being liberated from the high-pressure environment within a well.

Hazardous air pollutant (HAP): the US EPA defines HAPs as pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects.

Oil and natural gas (ONG): describing both liquid and gas fossil fuel products. Oil refers to crude oil hydrocarbon mixtures that exist in liquid form, whereas natural gas consists mainly of methane (CH_4), a small amount of hydrocarbon gas liquids, and nonhydrocarbon gases. Oil, gas, and liquid gas hydrocarbons can be found in underground reservoirs, sedimentary rocks, or tar sands and can be recovered in the near absence of the other forms or simultaneously.

Polycyclic aromatic compounds (PAHs): a class of organic compounds composed of multiple aromatic rings that occur naturally in crude oil. More than 100 different PAHs exist, including benzo[a]pyrene, benz[a]anthracene, and chrysene, with varying degrees of toxicity.

Petrogenic: originating from hydrocarbons formed by the decomposition of organic matter. In regard to petrogenic air pollutants, these may be released when fuel oil and crude oil are exposed during upstream oil and natural gas operations.

Polycyclic organic matter (POM): defines a broad class of compounds that generally includes structures containing 2–7 fused aromatic rings and are present in the atmosphere mostly in particle form. PAHs are a subset of POMs.

Proppant: a material (often sand) used to prop open cracks within fractured shale rocks to harvest oil, natural gas, or other targeted materials. Proppant is often mixed with a chemical liquid mixture and forced into shale formations at high pressure.

Reference effect level (REL): a reference exposure level from the Office of Environmental Health Hazard Assessment (OEHHA) of the California Environmental Protection Agency (Cal/EPA). The REL is a concentration of a single chemical at or below which adverse noncancer health effects are not anticipated to occur for a specified exposure duration. RELs have been developed for a limited number of compounds for acute, eight-hour, and chronic exposures.

Repository for Oil and Gas Energy Research (ROGER) database: PSE's nearly exhaustive database of peer-reviewed literature on shale gas development, which can be found on the PSE website (**http://www.psehealthyenergy.org**).

Wet gas: a natural gas that contains less than ~85% methane and increased amounts of ethane and other hydrocarbons, as opposed to dry gas, which occurs in the near absence of condensate or liquid hydrocarbons.

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2. MATERIALS AND METHODS

2.1. Scope

We began with the inclusion of all 187 HAPs listed by the US Environmental Protection Agency (EPA). Hydrogen sulfide (H_2S) was removed from the official US EPA list in 1991 but was included in our review owing to its toxic properties, detection at low concentrations (0.03–0.05 ppm), and prevalence in oil and gas development operations. From this point forward, when referring to HAPs, we include all 187 compounds listed by the US EPA, plus H_2S for a total of 188 compounds. Given the rapid expansion of ONG development activities over the past few years, only peer-reviewed articles published between January 1, 2012, and February 28, 2018, were included in the current review. Many HAPs have been measured and monitored near ONG operations as primary pollutants; however, some HAPs—including, for example, formaldehyde and acetaldehyde—are also secondary pollutants formed from the atmospheric transformation of precursor compounds emitted from ONG operations (27). Although they are central to the question of HAP formation and atmospheric concentrations, HAP precursors fall outside the scope of this review.

2.2. Keyword Search

We developed a list of keywords to assist in a comprehensive literature search of all upstream ONG processes and target pollutants. Owing to the inconsistency of the terminology surrounding the upstream ONG development process, we cast a wide net to be inclusive of possible iterations when building the keyword search. These keywords included, but were not limited to, the terms "fracking," "fracturing," "hydraulic fracturing," "oil and natural gas development," and common acronyms including "UNGD" and "ONG." In all, we incorporated 18 iterations and acronyms. Additionally, we included keywords for transport media to ensure that search results encompassed airborne compounds. We erred on the side of being overly inclusive and integrated broad group names, including volatile organic compounds (VOCs), nonmethane hydrocarbons (NMHCs), and hazardous air pollutants (HAPs) during the search process. Keywords and search queries are provided in **Supplemental Table 1**.

Supplemental Material >

2.3. Electronic Database Search

We searched peer-reviewed journal articles within three electronic search databases in March 2018. First, we searched the Clarivate Analytics Web of Science database (**http://www.webofknowledge.com**) using their Advanced Search query tool. Boolean operators were used to narrow English language article search results by topic and by publication timeframe. We also searched PubMed (**http://www.ncbi.nlm.nih.gov**) to ensure our literature review included a comprehensive search of peer-reviewed journal articles focused on the human health dimensions of upstream ONG development. Results were narrowed by text words and publication timeframe. Search queries resulted in 639 and 1,146 peer-reviewed journal articles in the Web of Science and PubMed, respectively. After comparing databases and eliminating duplicate articles, search results were then compared with PSE Healthy Energy's Repository for Oil and Gas Energy Research (ROGER) database (**https://www.psehealthyenergy.org/our-work/shale-gas-research-library/**). Articles found in the ROGER database that were not included in searches from the electronic databases were added to the collection, for a final count of 1,833 journal articles. These articles were then collected, organized, and evaluated using the inclusion/exclusion criteria.

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2.4. Inclusion and Exclusion Criteria

A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart shows how the inclusion/exclusion criteria resulted in the final article count (**Figure 1**). We first scanned titles to remove papers from our review on the bases of whether a paper met the following criteria: (*a*) not written in English; (*b*) was a review, commentary, or response paper and not a primary study; and (*c*) did not investigate air quality near ONG development. After reviewing the abstracts and content of the remaining papers, we excluded studies that did not collect primary, modeled, or estimated HAP emissions and concentrations or did not conduct other primary HAP analyses from secondary data sources. We focused on papers that described ground-level or local-level pollutant concentrations and papers that focused on source attribution of HAPs to upstream ONG operations. Several articles using concentrations of HAP compounds to model the formation of secondary non-HAP air pollutions were excluded if they did not directly investigate impacts of local-scale HAP compounds or their emission sources.

3. RESULTS

A total of 37 peer-reviewed journal articles, published between January 1, 2012, and February 28, 2018, met our inclusion/exclusion criteria (**Supplemental Table 2**). One peer-reviewed article focused on ONG operations in Poland, and the rest of the articles focused on operations within the United States. Thirty-one articles (84%) included primary HAP measurements within eight states, including Arkansas, Colorado, Ohio, Oklahoma, Pennsylvania, Texas, Utah, and Wyoming. The remaining articles included primary data analyses from secondary data sources or publicly accessible data sets.

Supplemental Material >

3.1. HAPs Identified Within Review

To enable generalization of results across all studies, we extracted the reported HAP concentrations from the article content, tables, or supporting information; we did not extract concentrations from graphs or figures. HAPs that were not found in the atmosphere above the sample limit of detection (LOD) were labeled as "Not Detected" (for additional information on the metric of interest, see the sidebar titled Metric of Interest: Sample Limits of Detection versus Health-Based Comparison Values). Of the 37 studies we reviewed, a total of 61 unique HAP compounds were measured near upstream ONG or investigated from secondary data sources. Forty-four HAPs

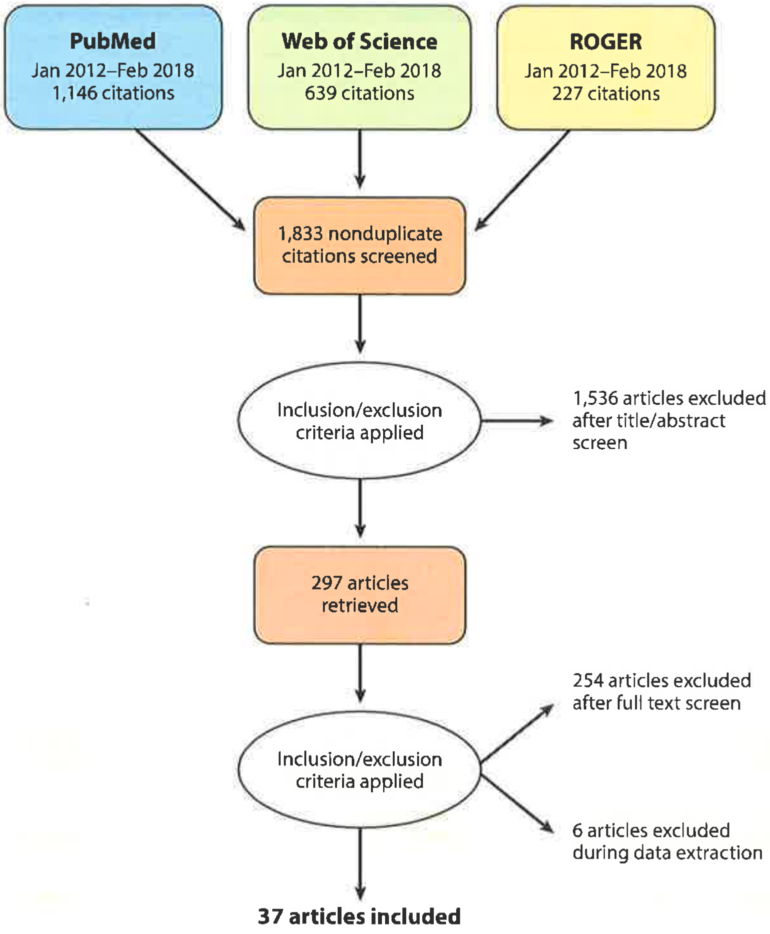

Figure 1

A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram for hazardous air pollutant (HAP) emissions near upstream oil and natural gas (ONG) development. Abbreviation: ROGER, PSE Healthy Energy's Repository for Oil and Gas Energy Research.

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were collected and reported in more than one article as primary or in-situ data, of which 32 were found above the sample LOD. **Supplemental Figure 1** provides the full inventory of HAP compounds investigated within the collected literature. HAPs collected from primary data sources were further listed by the state in which they were investigated and included in **Supplemental Table 4**.

Many of the peer-reviewed studies investigated a broad range of target analytes in ambient air, several of which are ubiquitous in the environment and are sourced not only in upstream ONG operations. While some of the HAP compounds listed in **Supplemental Figure 1** and **Supplemental Table 4** may have a source in upstream ONG, without point source or source attribution methodologies, their association is speculative. Therefore, in the following sections, we have further assessed the 61 HAP compounds identified within the peer-reviewed literature to classify pollutants assessed for contributing sources and to determine their potential association with upstream ONG development.

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METRIC OF INTEREST: SAMPLE LIMITS OF DETECTION VERSUS HEALTH-BASED COMPARISON VALUES

The sample limit of detection (LOD) expresses the lowest concentration of the targeted analyte that can be distinguished within a given sample, instrument, or method. We use the sample LOD as our metric of interest instead of commonly referenced health-based comparison values for several reasons. First, the heterogeneity of sampling methodologies prevents direct comparison between concentration results (6). Second, it is difficult to select a single health-based standard exposure timeframe that adequately represents the variety of sampling durations present in the reviewed literature (**Supplemental Table 3**). Finally, many health-based standards are derived from limited data sets and inadequate conversion factors that do not appropriately define the risk threshold of sensitive populations nor do they address the risks of exposure to multiple HAPs concurrently and, thus, may inappropriately imply the absence of health risks.

Despite these advantages, an LOD above health-based standards may erroneously imply low exposure risk when concentrations are not detected within the sample. To address these issues, we advise researchers to include LODs within the results to avoid misleading the reader. Failure to supply sample LODs encumbers accurate descriptions of atmospheric concentrations, leading to underestimations of exposure, an issue we have found rife in the ONG literature.

Supplemental Material >

3.2. Sources of HAP Emissions

The range of air pollutant emission sources identified in the reviewed literature includes equipment (e.g., dehydrators, condensate tanks), activities (e.g., flashings, gauging flowback tanks), development phases (e.g., drilling, well stimulation), and facilities (e.g., flowback and produced water treatment and recycling center, oil storage facility). To simplify these broadly categorized emission sources, we recategorized equipment, activities, and facilities into one of the four most appropriate upstream ONG phases: (*a*) exploration and well pad and infrastructure construction; (*b*) well drilling and construction of associated facilities; (*c*) well stimulation, enhanced oil recovery, and completion; and (*d*) ONG production and processing. For example, air quality measurements collected from flowback were recategorized into the third phase (well stimulation, enhanced oil recovery, and completion) because flowback is a fluid often recovered as a result of well stimulation (e.g., hydraulic fracturing). Storage tanks and impoundments can be present at the well pad through multiple phases or can be transported off-site via trucks or pipeline networks. Since the location of storage-related equipment and associated activities varies by location, HAP compounds identified from these sources have been recategorized into a separate storage and impoundment phase and described in Section 3.2.4.

Point source data are collected from stationary, identifiable locations and equipment that release pollutants into the atmosphere. Studies that included the collection of on-site primary point source air quality data, including Brantley et al. (15), Esswein et al. (39), and Hildenbrand et al. (58), provided detailed information about the equipment and activities that occurred during their sampling periods. On the basis of these detailed descriptions, we collected and recategorized the reported data into one of our five phases. In the absence of identifiable emission points, source attribution methods are important to estimate probable sources or categories of sources. Examples of source attribution methods employed in the reviewed literature include factor analyses (1, 43, 90), distance decay gradients (125), and sourcing ratios (45, 46, 50, 54, 85, 99), among others. Additional studies, including Macey et al. (73) and Colborn et al. (27), collected samples off-site and provided information about potential emission sources by detailing the most proximate upstream

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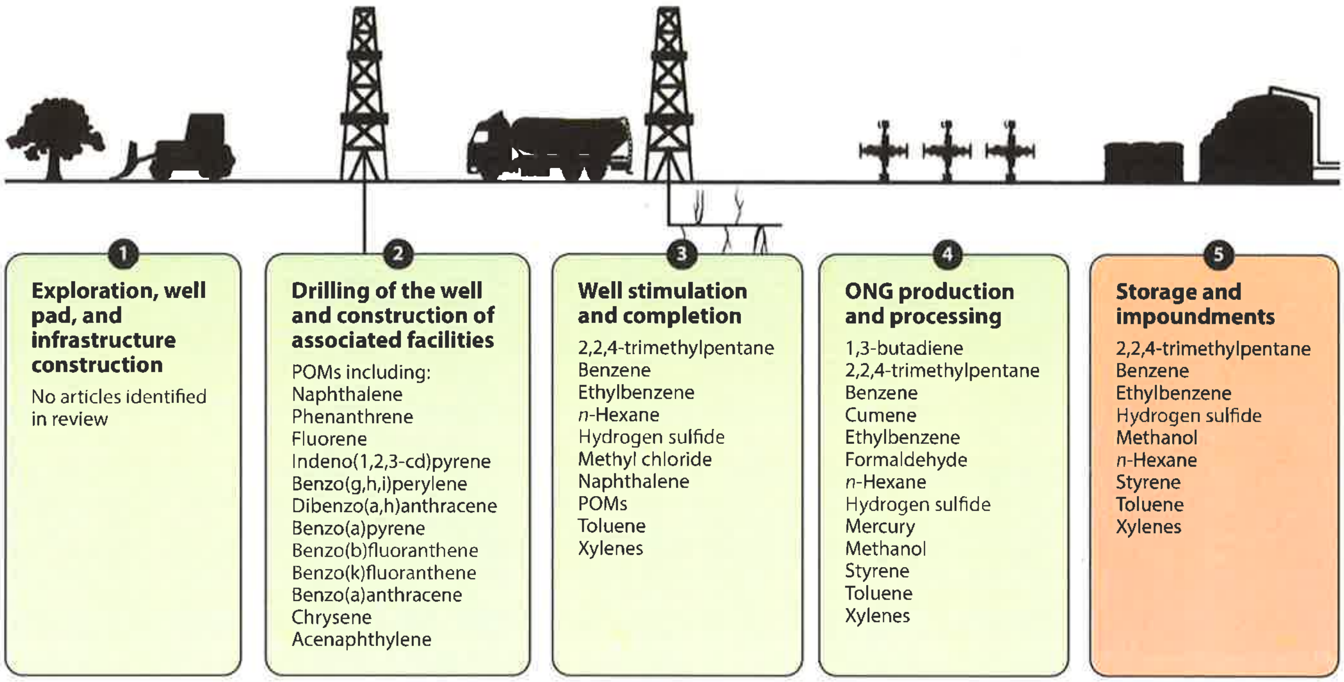

Figure 2

Hazardous air pollutant (HAP) compounds collected through primary measurements and recategorized. Abbreviations: ONG, oil and natural gas; POMs, polycyclic organic matter.

ONG equipment or activities during the data collection timeframe but did not specifically apply commonly used source attribution techniques. Recognizing the limitations of off-site activity reporting in the absence of well-established source attribution analyses, we cautiously used these descriptions as a guide for recategorization but used our best discretion for inclusion.

A complete summary of recategorized HAP emissions from primary measurements within the reviewed literature is provided in **Figure 2**. We did not identify any HAPs that were sourced to emissions during the first phase of development (exploration and well pad and infrastructure construction).

3.2.1. HAP emissions from well drilling and construction of subsurface infrastructure.

After the site has been cleared and a well pad is established, a vertical well is drilled often using gas-powered rigs and other ancillary equipment to reach depths of several hundred meters below the surface. If necessary, operators will continue to drill directionally (e.g., horizontally) to increase the surface area of the target petroleum geologic zone (e.g., in the case of shale gas development). Drilling through intermediate geological formation on the way to the target formation may release trapped hydrocarbons that can migrate to the atmosphere (23, 51). Thus, both ancillary drilling equipment and subsurface pockets of gaseous fluids within intermediate geologic formation are a source of various HAP emissions into the ambient environment during the drilling and well construction phase (17).

Colborn et al. (27) measured the most elevated chemical concentrations in the ambient air from a stationary monitoring site located 1.1 km from a well pad during drilling activities in rural Colorado. Samples identified twelve different polycyclic aromatic hydrocarbon (PAH) compounds, a subset of polycyclic organic matter (POM) compounds, during a timeframe dominated by drilling activities. Elevated carbonyl and VOC concentrations were also detected; however, the individual VOC species were not detailed within the paper and, thus, are not included in this section. Source attribution using temporal patterns of PAH concentrations in the ambient environment without supplementary sourcing analyses is difficult to interpret, especially for PAHs that lack chemical disclosures or inventories as well as PAHs commonly formed from combustion or other anthropogenic sources. Yet, analyses of similar PAH compounds found evidence of petrogenic sources during a range of upstream ONG activities in Ohio (85); thus, we have included these within the current section. Additional mobile measurements in Pennsylvania detected acetaldehyde, acetonitrile, benzene, methanol, and toluene downwind from a drilling rig; however, concentrations were not elevated above background, suggesting that the rig was not operating at full capacity, the emissions from this activity in this particular geographic and geologic area did not have high emissions, or the activities and equipment associated with the drilling phase were not the source of these pollutants and thus were not included in our sourcing analyses (51).

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3.2.2. HAP emissions from well stimulation, secondary recovery, and completion.

The well completion phase encompasses all processes associated with preparing a newly drilled well for the production of oil and gas. This phase is relatively short in duration (3–15 days) but can include a variety of activities, including flowback collection, flaring, workovers, and completion venting. Once the well is drilled, cement and casing are installed to stabilize the wellbore and provide zonal isolation to minimize subsurface migration of liquid and gaseous fluids. This step is followed by the perforation of the casing in the target hydrocarbon reservoir to allow for the stimulation and other injected fluids to gain access to the petroleum reservoir and then subsequently for the flow of hydrocarbons into the well. In low-permeability reservoirs, where hydraulic fracturing and other stimulation are required to extract hydrocarbons, between 0.25 and 50 million gallons of water, chemicals, and proppant are injected down the well at a pressure high enough to increase the permeability of the target geology. The return of these stimulation fluids to the wellhead is referred to as "flowback." Although chemical constituents from the geological formation are present in this flowback, these fluids are often opaquely distinguished from "produced" water, which surfaces shortly thereafter and often throughout the lifetime of active hydrocarbon production (13). Because flowback is limited mostly to the current phase, we include emissions associated with flowback, and not produced water, which is reviewed in subsequent sections. It should be noted, however, that scientific distinctions between the flowback and produced water phases of oil and gas development are not specific and vary considerably across geological and regulatory spaces (70).

BTEX, 1,3-butadiene, n-hexane, cumene, styrene, and 2,2,4-trimethylpentane were identified around the perimeter of five well pads in Colorado during completion activities and, with the exception of styrene, cumene, and 1,3-butadiene, median concentrations were higher than background in ONG area samples (79). Field sampling downwind of a well pad in Pennsylvania during flaring activities measured benzene, toluene, and n-hexane above the sample LOD and at concentrations higher than the upwind direction (76). Occupational and off-site measurements identified POMs (including naphthalene) and H_2S near flowback and workover rigs (39, 73).

BTEX compounds and n-hexane are found in diesel combustion emissions from equipment and vehicles used in ONG, drilling fluids, and fracturing additives. BTEX compounds, in particular, occur naturally in oil and gas geological formations, and emissions of these compounds during oil and gas development are likely attributable to various processes, including those that provide an opportunity for gas compounds to migrate to the surface and volatize into the ambient air. Therefore, many of the HAPs identified in ambient air near ONG operations during well stimulation and completion could be direct emissions from ancillary well pad equipment, loss of wellbore integrity, improper handling of flowback fluids, and volatilization from the chemical mixtures used for stimulation fluids or completion activities (61, 101, 108, 109). With the current evidence, we cannot identify the specific source activity or equipment, although ONG development appears to be a likely source of these compounds identified at elevated concentrations in the ambient air.

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3.2.3. HAP emissions from oil and gas production and processing. During the production phase, ONG is collected from the well and processed with various ancillary equipment, including wellhead compressors, pneumatic devices, separators, and dehydrators. The production phase is the longest of all the upstream phases with the potential to emit maximum peak values that exceed the stimulation and completion phase (17), and it was linked to the most varied number of HAPs within our review. While a given shale well may be depleted within 1–5 years, migrated oil reservoirs may produce for decades. Hydrocarbon production in geological zones richer in oil and wet gas may be associated with HAPs and other larger-molecular-weight hydrocarbon emissions during the production and processing phase when target alkanes are separated from heavier compounds. Operational practices, the spud date, the petroleum geology, and production volumes can also heavily impact emissions from producing wells within the same shale play (51, 98). Therefore, without insight into reservoir composition and well pad operations, it is difficult to predict the geography and magnitude of HAP emissions or to extrapolate results to larger areas.

Wellheads, dehydrators, and separators are important sources of elevated HAP emissions during production and processing in regions rich in oil, wet gas, and condensate (43, 112). Dehydration units account for an estimated 40% of HAP emissions (36). Point source measurements collected on a well pad in Colorado identified BTEX compounds, styrene, n-hexane, and 2,2,4-trimethylpentane near producing wellheads, dehydrators, and separator units (15). Off-site measurements in Texas and Wyoming identified similar emissions with an addition of cumene and H_2S near wellheads, separators, and produced water tanks and discharge canals (35, 73). Compressors used to maintain hydrocarbon flow were associated with emissions of BTEX compounds, 1,3-butadiene, methanol, formaldehyde, mercury, and n-hexane (35, 51, 65, 73, 75, 90). With the exception of mercury, these compounds are commonly emitted from continuously reciprocating natural gas–fired engines, and their presence within the collected samples was not unexpected. A report analyzing point source emissions data from 58 compressor stations found formaldehyde to be the fourth largest chemical released by compressors by total pounds, just after total VOCs (92). Mercury, a trace component in natural gas condensate, is removed from the compressor process; thus, its emission may actually be a result of ineffective mercury removal systems and therefore is included in this phase (65).

Abnormal process conditions including control failures, design failures, and malfunctions upstream of the point of emission occur in only a small fraction of facilities, yet they may be responsible for a significant portion of ONG-related air pollution (16, 30, 59, 123). Flyover measurements in the Haynesville and Marcellus Shale gas production regions found that only ~10% of facilities were responsible for up to ~40% of the total CH_4 emissions emitted from these operations (120). Although these measurements might not be representative of all associated HAP emissions, enhancement ratios and correlations between CH_4 and benzene suggest a similar source. Furthermore, mobile measurements in the Barnett Shale area found that only 4% of measured ONG facilities were responsible for a relatively large amount of the measured atmospheric mercury (65). Within the current review, few air quality samples were reported as collected during abnormal ONG development process conditions, yet it is possible that off-normal events occurred without operator knowledge or public disclosure. For example, samples collected near production phase equipment described as "rusty" recorded HAP concentrations up to 47 times higher than those described as being in "good" operating condition, yet neither were identified as abnormal processes (15). In the instance where infrared video captured a clear example of a leaking natural gas

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wellhead, elevated concentrations of benzene, xylenes, n-hexane, and toluene were detected on- and off-site and near residential homes (40).

3.2.4. HAP emissions from storage tanks and impoundments. Storage tanks and impoundments are often used to hold production and maintenance chemicals or condensate and recovered fluids collected and separated during various phases. Chemicals stored at upstream ONG sites include chemical additives and mixtures for well stimulation and various well and equipment maintenance needs. Condensate is different from stored chemicals, flowback, and produced water in that it has been separated from extracted crude oil or natural gas matrices in preparation for additional processing or disposal. Emissions from storage and condensate tanks have been associated with H_2S, BTEX, n-hexane, styrene, methanol, and 2,2,4-trimethylpentane (15, 67, 112). Many of the stored liquids are volatile and enter a gaseous phase as a result of increases in temperature and decreases in pressure. Workers in the upstream ONG industry, especially those working with flowback and condensate tanks, are at increased risk of exposure during routine gauging, measurement, and oil flashing activities, which provide an opportunity for stored liquids to volatilize and escape into the atmosphere. A number of occupational deaths have been reported among workers taking volume measurements of condensate tanks (55).

Such condensate tank emission events, even if brief, can be significant, which may have a substantial impact on local air quality (46), especially in oil-producing areas (72). Storage tanks can be housed at the well site that provide additional emissions source points during the associated phase; however, they can also be sited at different locations, far from the well pad, or piped off-site through transmission pipeline networks (45). Many of the listed HAPs in this section were found at well pads during production, but they were recategorized into the current separate group as the location of storage equipment and related activities varies by well site.

3.3. Summary of Health Impacts from HAP Compounds

HAP compounds are associated with multiple cancer and noncancer health outcomes and have, in some studies, been detected near ONG sites at levels that exceed health-based standards and reference concentrations. The current ONG literature offers limited insights into specific etiological agents and health outcomes because granular measurements of exposure have largely not been undertaken. To better understand health risks and impacts from HAP exposures near upstream ONG development, we further evaluated the studies that included a health component in the analysis. Although exposure to any of the 188 listed HAP compounds may pose reason for concern, we identified several HAPs that were consistently found to be above sample LODs or above health benchmarks or that posed the highest risk from inhalation exposures. A summary of some of the key findings is provided in the following sections.

3.3.1. HAPs of highest concern. BTEX compounds are associated with several serious human health impacts, including neurological damage, birth defects, some cancers, and hearing loss (117). Ubiquitous in the environment, these compounds commonly exceed sample LODs in urban areas as a result of transportation and industrial processes (11); however, many of the reviewed samples were collected near ONG activities in rural regions, where urban emission sources are likely to have minimal impact on local and regional ambient air quality. Several of the studies included in this review found rural BTEX concentrations to exceed those measured in dense urban areas and at concentrations that exceed health-based standards, with some concentrations over 2,900 ppb (parts per billion) (37, 43, 45, 46, 48, 51, 54, 73, 88, 91, 99, 102, 112). For reference, the Office of Environmental Health Hazard Assessment (OEHHA) acute reference effect level (REL)

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in nonoccupational settings for benzene is 8 ppb, and the 8-hour and chronic RELs for benzene are 1.0 ppb (29). Studies that report ambient BTEX concentrations below existing health-based standards have implied that upstream ONG emissions of these compounds may not have a substantial impact on human health, yet ambient BTEX concentrations, below health benchmarks, have been associated with adverse health outcomes in numerous epidemiological studies (2, 3, 7, 33, 47, 63, 64, 69, 71, 74, 87, 119, 121, 124).

While health-based air quality standards provide a guide on which to base regulatory thresholds, many standards are extrapolated from in vivo or in vitro animal studies or human-based occupational studies that may not be appropriate for the protection of sensitive populations such as children and pregnant women (42, 110, 113). Recognizing the possible inadequacies of existing uncertainty factors for benzene, the OEHHA in California recently applied a stricter REL to include additional protections to sensitive populations (29), yet questions remain over whether these updated standards are protective enough. On the basis of the existing evidence of exposure risks from chronic, low-level concentrations, current noncancer health benchmarks, such as the OEHHA RELs, may be insufficient for estimating health impacts from benzene-related exposures near upstream ONG development. Recognizing the cancer risks associated with benzene exposures, the World Health Organization states that "no level of exposure can be recommended," implying that there is likely no safe lower threshold of exposure as implied by the RELs (116).

Formaldehyde and acetaldehyde were found to be the most abundant carbonyl species when sampling ambient air near ONG facilities. The chronic OEHHA nonoccupational RELs for acetaldehyde and formaldehyde are 80 ppb and 7 ppb, respectively (84). While many of the observed concentrations around ONG operations were below health standards, the International Agency for Research on Cancer has classified formaldehyde as a group 1 carcinogen, meaning it causes cancer in humans (8) and, generally, does not have a threshold below which there is a safe level of exposure. Furthermore, simplified health risk assessments and modeling estimates near ONG activities have suggested that formaldehyde and acetaldehyde are the dominant contributors to cancer risks (25, 99). The abundance of formaldehyde detection in ambient collected samples may actually indicate secondary atmospheric formation as the dominant source and not primary emissions released directly from an ONG point source. Mandated state inventories that focus on primary emissions may actually lead to underreporting if secondary atmospheric formation is the dominant pollutant source.

The natural gas and crude oil impurity H_2S is a colorless and flammable toxicant easily identifiable by its rotten egg odor. H_2S becomes detectable at concentrations as low as 0.5 ppb (10), becomes chronically toxic at 8 ppb (83), and has a National Institute for Occupational Safety and Health (NIOSH) immediately dangerous to life or health (IDLH) concentration of 100 ppm (24). Within the current review, H_2S has been measured in ambient air at various phases of upstream ONG development, including during separation, in storage tanks, and in discharge canals at concentrations exceeding those known to be safe (35, 39, 67, 73). Concentrations of H_2S above the odor threshold were measured just beyond the fence line in 8% of natural gas production sites in Texas during mobile measurements (35).

The simplest unsaturated aldehyde, acrolein, is fairly ubiquitous throughout the environment at concentrations above chronic noncancer benchmarks (77, 81, 100, 118). Used as a biocide additive and H_2S scavenger in ONG operations, acrolein is also emitted from more common sources, including incomplete combustion of petroleum products, tobacco smoke, and cooking activities. Owing to the current health burden of exposure in the ambient environment, the OEHHA identified acrolein as one of the top five most important pollutants of concern in California (4), and an additional exposure from ONG operations could compound the existing public health burden.

Acrolein is difficult to measure accurately, and controversy over prevailing sampling methods persists (49, 57, 62). Exposure to acrolein may cause adverse health effects, including eye, nose, and throat irritation, chest pain, and difficulty breathing (9). In California underground natural gas storage facilities, acrolein is reported as the eighth highest emitted air pollutant in California and was found at elevated levels in indoor environments near the site of the Aliso Canyon natural gas storage blowout (66, 94). Acrolein plays a substantial role in the upstream ONG process, and yet methodological constraints limit the availability of reliable industry-related emissions estimates and, consequently, obscure the understanding of the potential impact to human health.

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3.3.2. Gaps in health research. Recent health-based studies have uncovered a spatial relationship between upstream ONG and a range of health outcomes. Epidemiological and health-based studies have found increased risk and incidence of adverse birth outcomes near ONG activity compared with further away (22, 31, 60, 96). Similarly, studies that utilize distance metrics as proxies of exposure reported increased health risks for individuals living near ONG activity compared with further away (21, 79, 99). These findings are corroborated by symptom surveys that found that the number of reported symptoms was higher among residents living closer to well pads compared with those living further away (97). Moreover, McKenzie et al. (78) paired in-situ air quality measurements with distance and cancer risk assessment. The study found that within 152 m (~500 feet) of active oil and gas development, the cancer risk estimate was 8.3 cases per 10,000 individuals, greatly exceeding the US EPA's upper threshold for acceptable risk (1 excess case in 10,000).

Despite findings of a spatial dimension of health data near upstream ONG development, measured pollutant concentrations, including concentrations of HAPs, were generally below health-based standards. It is unclear why ambient air samples have failed to capture concentrations above health benchmarks while the majority of epidemiological studies continue to find incidence of poor health outcomes increasing as distance from these operations decreases. Recent literature provides insights into methodological shortcomings that make investigations more prone to null air pollutant concentration findings. First, in-situ measurements of emissions collected at a distance from well pad activities are prone to effects of atmospheric degradation, dispersion, and deposition (86), and yet they are commonly, and inappropriately, extrapolated to describe local exposures. Studies that utilize data from standard air monitoring networks, such as the Texas Commission on Environmental Quality (19, 40, 93), may fail to capture concentrations that pose actual exposure risks as a result of such methodological biases.

Second, samples collected with short collection timeframes (e.g., "grab samples") are capable of detailing only conditions at a particular—and short—moment in time and often fail to capture the episodic peaks commonly associated with many of the upstream ONG development processes (17). Similarly, integrated concentrations derived from longer sampling timeframes may dilute elevated concentrations during peak emission events and, thus, underestimate the full range of potentially recurring acute exposures (54). Recent evidence suggests that abnormal process conditions or uncontrolled emission events from a small proportion of wells or associated ancillary infrastructures may better explain the complex exposure environment from local to regional scales (123). Studies that estimate exposures on the basis of modeled emission masses and rates may miss peak exposures from abnormal process conditions that are more accurately characterized via field sampling. Air quality studies that focus on granular geographic estimates of exposures via continuous, local-level monitoring better characterize ambient concentrations during brief peak emission episodes, common in upstream ONG development, that may be missed using intermittent sampling methods at select stages (28, 54).

Third, the current state of toxicological data and exposure science may not adequately address potential risks associated with long-term, chronic, lower levels of exposure, particularly when multiple air pollutants might be implicated (18, 20, 52). Thus, available health standards developed from inadequate uncertainty factors may not provide protection for human populations and especially for sensitive subpopulations, including infants, children, pregnant mothers, and people with preexisting medical conditions. Using OEHHA's conservative list of approved risk assessment health values as a guide to understand the current state of available health benchmarks (5), we found that fewer than 40% of all HAP compounds had inhalation cancer risks or noncancer health-based exposure levels. Several compounds that lack reference values were detected in air near, and are likely associated with, ONG sites. Other contaminants with health benchmarks, such as benzene, may still elicit health effects at concentrations lower than the REL. Furthermore, many HAP compounds are associated with cancer end points that, even at low atmospheric concentrations, generally do not have a threshold below which there is a safe level of exposure. Therefore, health studies that provide only comparisons to noncancer benchmarks may be misleading in their estimates of actual long-term health impacts.

Finally, health studies that use single pollutant health-based standards may fail to provide accurate risk estimates from concurrent or close-succession exposures to multiple pollutants that may act biologically antagonistic, synergistic, or additive (105). This situation of potential exposures to multiple air pollutants is particularly relevant for upstream ONG development where emission inventories and air quality monitoring have identified a wide range of pollutants that are often coemitted. Without knowledge of a specific etiological agent or exposure pathway, investigators may find that these studies fail to sample and analyze the full range of biologically relevant ONG pollutants or determine the most appropriate exposure pathways.

4. DISCUSSION

We identified 37 peer-reviewed journal articles that met our inclusion/exclusion criteria, of which all but one focused on ONG operations within the United States. In our review, we found a lack of peer-reviewed literature from outside the United States, likely owing to the growing concerns about human health and environmental impacts, which may have slowed adoption of novel extraction methods in other countries. With the exception of Russia, the United States produced at least twice as much natural gas compared with all other regions in the world (103). In Europe, most exploratory shale gas extraction has occurred in Poland and the United Kingdom, but France and Norway have some of the most promising reserves that remain largely unexploited (44). Within the collected literature, we identified 61 HAPs, of which only 32 were collected during in-situ monitoring. Hydraulic fracturing has received the greatest attention for its potential impact to human and environmental health (14). In the context of HAPs, however, we did not find evidence to support the common assumption that the discrete hydraulic fracturing phase itself is associated with the highest risk of exposure. Instead, we found that the production phase—with its lengthy operation timeframe, episodic peak emission events, and largest number of HAPs sourced to the various equipment and operations—has the potential to emit the highest concentrations and the most varied mixture of HAPs over the longest time period, especially in regions rich in oil, wet gas, and condensate. Our review of the literature further suggests that exposure risks can be much higher if production equipment is colocated with condensate storage and wastewater impoundments. ONG development does not necessarily involve hydraulic fracturing but may include a myriad of different oil and gas development techniques, many that were not investigated within the collected literature.

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In general, in-situ air pollutant measurements were found to be below health benchmarks, and yet multiple health-based studies found evidence of a spatial relationship between concentrations of HAPs and incidence of cancer and noncancer health end points in the context of proximity to oil and gas development operations. These findings suggest several possible explanations: (*a*) Spatial sampling methodologies fail to properly characterize exposures prior to atmospheric degradation, dispersion, and disposition of sampled pollutants; (*b*) ambient air sampling timeframes are inappropriate for capturing the episodic peak emission events characteristic of upstream ONG; and (*c*) prevailing health benchmarks are inadequate to identify exposures to chronic, low levels of pollutants, multiple chemical exposures or from multiple exposure pathways.

This review has several limitations. First, some HAPs targeted for this review include broad-range categories (e.g., POM) that contain multiple constituents of varying degrees of toxicity, of which some may have been overlooked during the inclusion/exclusion review. Second, some activities and equipment are used in both upstream and midstream (e.g., hydrocarbon transport) processes, and it was not always clear which was being measured when in-situ monitoring data was being collected. For example, compressors can be used to transport hydrocarbons and other compounds off the well pad during upstream activities, but the act of transportation would classify associated releases as midstream emissions. We used our best judgment when collecting and recategorizing HAP compounds; however, without clarification from the studies' authors, we may have included some midstream processes in our reclassification efforts. Third, several studies included in our review suffered from methodological limitations resulting in over- or underestimated concentrations of summary findings. Although we attempted to recognize and address these inadequacies we may not have adjusted for all possible shortcomings in the reviewed literature. Fourth, we used sample LODs as the most appropriate metric of interest because the heterogeneity of sampling methodologies limited direct comparisons of measured or estimated concentrations across studies (for more information, see the sidebar titled Metric of Interest: Sample Limits of Detection versus Health-Based Comparison Values). While it would be helpful to consider sample LODs when evaluating nondetected HAPs, we identified a consistent failure to supply sample detection limits within the peer-reviewed literature in this review. Finally, our review was limited to constituents classified as HAPs; non-HAP compounds were beyond the scope of this article. Similarly, HAP compounds that were excluded from the collected literature were not extensively discussed here. By design, this review was limited to a select group of compounds that have been previously studied within the peer-reviewed literature. However, non-HAP compounds, HAP compounds not measured, and HAP compounds found under the sample LOD may still have a significant role in upstream ONG development and should be investigated in future studies.

Through our synthesis of the peer-reviewed literature, we have identified the following research priorities: (*a*) Increase research of HAPs near upstream ONG development with an emphasis on those that have not been extensively measured or reported on in the peer-reviewed literature, especially those that overlap with chemicals identified in state inventories or disclosures; (*b*) undertake detailed source attribution investigations of emissions using spatially and temporally appropriate measurements; (*c*) conduct detailed health studies that focus on granular estimates of exposures near upstream ONG development via personalized and community-based monitoring; and (*d*) implement additional research on health impacts from chronic, low-level ambient HAP exposures. Adoption and implementation of these research priorities will help guide future policy aimed to implement appropriate upstream ONG development emission control measures that will protect human and environmental health and decrease the adverse impacts of upstream oil and gas development.

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DISCLOSURE STATEMENT

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Environmental Concerns for Children with Asthma on the Navajo Nation

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Abstract

Rationale: Navajo children living on the reservation have high rates of asthma prevalence and severity. Environmental influences may contribute to asthma on the Navajo Nation and are inadequately understood.

Objectives: We performed a comprehensive, integrative literature review to determine the environmental factors that may contribute to increased asthma prevalence and severity among Navajo children living on the reservation.

Methods: A systematic search was conducted in four databases regarding the environmental risk factors for asthma in Navajo children living on the reservation. Relevant studies between 1990 and 2017 were examined. Nonexperimental literature was also integrated into the review to describe the environmental injustices that have historically, disproportionately, and systematically affected the Navajo people, thus contributing to respiratory disparities among Navajo children.

Results: Eight studies met inclusion criteria for systematic review; however, limited research regarding environmental risk factors specific to asthma and Navajo children living on the reservation was identified. Our integrative review indicated both indoor and outdoor environmental risk factors commonly found on the Navajo reservation appear to be important determinants of asthma.

Conclusions: Future research should examine indoor and outdoor air pollution from wood-burning stoves and cook stoves, coal combustion, tobacco and traditional ceremonial smoke, diesel exhaust exposure from long bus rides, indoor allergens, ambient pollutants, and regional dusts. Comprehensive mitigation efforts created in partnership with the Navajo Nation are necessary to address less-recognized risk factors as well as the common risk factors known to contribute to increased childhood asthma prevalence and severity.

Keywords: Navajo; American Indian; Native American; asthma

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Despite perceptions to the contrary, asthma rates are not lower in rural as compared with urban populations, and exposure to indoor and outdoor pollution not typical in urban environments may increase pediatric asthma prevalence and severity (1, 2). Approximately 13.0% of American Indian/Alaska Native children have asthma, as compared with 8.6% of children in the U.S. general population (3). Asthma morbidity also appears to be higher among American Indian/Alaska Native children, with 67.3% reporting an asthma attack in the past 12 months, as compared with 60.7% of the U.S. general population (3). In 2013, the Navajo Nation Epidemiology Center surveyed the Chinle Agency and found that 14.2% of respondents reported ever having been told by a health professional they had asthma, and 11.0% having a current as

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Health disparities for American Indian/Alaska Native children with asthma living on the reservation include poverty, limited access to specialty care, and environmental challenges, which include high levels of indoor and outdoor air pollution.

The Navajo reservation is located in the southwestern United States and spans a geographic area of more than 27,000 square miles (5). The reservation is positioned across six counties and three states and consists of multiple U.S. census blocks, which presents numerous challenges with epidemiological data collection and analysis (6). Tribal-specific data composed by the U.S. government are limited, and most data collected by the Navajo Nation are not publicly available to researchers. The Navajo Nation is the most populous of all Indian Nations, with more than 250,000 individuals; approximately 44% of the Navajo population are children younger than 19 years of age ($n = 117{,}769$) (5, 7). The southwest Indian Health Services region, which includes the Navajo Nation, reports the highest rates for asthma hospitalizations among the six Indian Health Services regions (10.0 per 10,000 population; range, 1.8–10.1 per 10,000 population) (8).

The physical environment on the Navajo reservation may disproportionately expose children to risk factors for increased childhood asthma prevalence and severity. Indoor use of wood-burning stoves is suspected to be common; otherwise, information about potential asthma-relevant environmental determinants remains sparse. In this review, we sought to integrate the known literature on indoor and outdoor air quality specific to the Navajo reservation and highlight the issues that impact these risks, while acknowledging the historic impact of environmental injustices that may influence increased pediatric asthma prevalence and severity among Navajo children living on the reservation.

Methods

A protocol adapted from PRISMA (Preferred Reporting Items for Systemic Reviews and Meta-Analyses) guidelines (*see* Table E1 in the online supplement) was developed to systematically guide the abstract selection process. A comprehensive search was conducted in four databases (Table 1). Abstracts yielded by the search were scanned by both the primary author (A.A.L.) and senior author (L.B.G.). We selected articles for full review if they met the following inclusion criteria: *1*) a peer-reviewed study, *2*) published in the English-language, *3*) the target population was the Navajo Nation or American Indian/Alaska Native (AI/AN), *4*) content was specific to asthma or chronic respiratory illnesses, and *5*) research addressed an indoor or outdoor environmental risk factor of asthma or respiratory disease. The primary reason articles were excluded from full review was that the content did not address an environmental risk factor of childhood asthma on the Navajo Nation or in an AI/AN population. A hand search was also conducted by reviewing the reference lists of articles as well as consultation with experts in the field. Figure 1 illustrates the abstract and full-text selection process of articles included in this review. The last search was completed on November 1, 2017. Where no peer-reviewed literature was found, we briefly discussed potential indoor and outdoor environmental risk factors as suggested by the non-AI/AN– and non-Navajo–specific literature.

Table 1. Databases and full electronic search strategy for systematic search

Database	No. of References	Full Electronic Search Strategy
PubMed (1966–present)	71	("asthma"[Mesh:NoExp] or asthma[ti] or "respiratory illness") AND ("indians, north american"[Mesh] OR "native americans"[tiab] OR "southwest"[tiab] OR "navajo"[tiab] OR "Navaho"[tiab] OR "dine"[tiab] OR "dineh"[tiab])
Latin American and Caribbean Health Sciences database (LILACS) (1980–present)	0	American Native Continental Ancestry Group AND Asthma OR Respiratory Illness
Web of Science (1900–present)	135	TOPIC: (asthma OR respiratory illness) AND TOPIC: (native american OR native americans OR american indians OR navaho OR navajo OR dine OR dineh OR southwest)
Education Resources Information Center (ERIC) (1965–1998)	14	(navajo OR navaho OR diné OR dineh) AND (diesel OR bus OR buses OR busing OR pollution OR emissions OR asthma)

Definition of abbreviations: ERIC = Education Resources Information Center; LILACS = Latin American and Caribbean Health Sciences database.

Results

Out of 220 screened abstracts, only 8 articles met our inclusion criteria for review. Four articles were specific to the Navajo population, and four included all AI/AN (Table 2). Table 3 summarizes the environmental exposures (i.e., indoor and outdoor) suspected of affecting asthma development, severity, and exacerbation among children.

Indoor Air Quality/Exposures

There is ample literature investigating the connection between indoor air pollution and poor respiratory health. Particulate matter (PM) less than or equal to 2.5 μm in aerodynamic diameter ($PM_{2.5}$) and PM less than or equal to 10 μm in aerodynamic diameter (PM_{10}) are associated with asthma severity and morbidity and acute lower respiratory infection (9, 10). Indoor pollution poses a great risk to children because of their increased respiratory rate, developing immune systems, and narrower airways (11).

Wood-burning stoves. Approximately 49% of homes lack electricity on the Navajo reservation, and 89% of Navajo families rely on biomass combustion as an economic and primary source of heat (6, 12). Prior research indicated that children residing in rural locations without access to clean fuels have higher mortality rates than children residing in rural locations with cleaner fuels (13), and exposure to indoor combustion sources increases the risk of asthma and asthma severity in children (14). Toxic pollutants including PM, carbon monoxide, oxides of nitrogen, and volatile organic carbons are present in wood smoke (15). In addition, wood-burning stoves are sometimes used to burn alternative materials for heat, which may increase the health-damaging effects of indoor air pollution. A survey conducted by

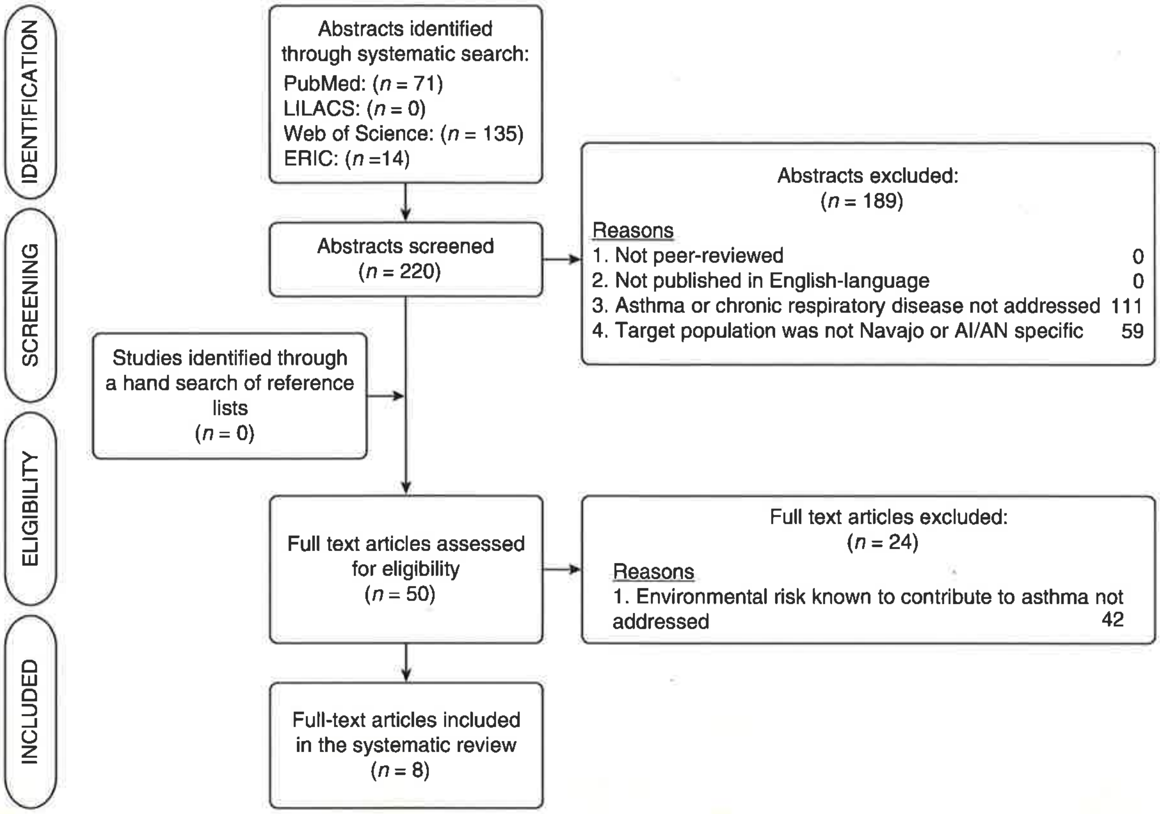

Figure 1. Flow chart of systematic integrative review process. AI/AN = American Indian/Alaska Native; ERIC = Education Resources Information Center; LILACS = Latin American and Caribbean Health Sciences database.

Bunnell and colleagues found that 77% of Navajo homes (*n* = 137) used an indoor woodstove for heating, and 25% of homes burned coal in woodstoves not designed for higher combustion temperatures. Ninety-one percent of these stoves had visible cracks, fissures, holes, or insufficient ventilation, and 26% of these stoves were more than 10 years old (16).

Yet, there is limited research specific to Navajo children regarding indoor wood stoves and their impact on asthma, despite the large proportion of reservation families that rely on biomass combustion for domestic heat. Our systematic search revealed two studies specific to Navajo children that discussed woodstoves, indoor biomass combustion, and respiratory infections. Morris and colleagues investigated wood-burning stoves and lower respiratory tract infections in Navajo children 24 months of age or younger (17). Fifty-eight children with diagnosed pneumonia or bronchiolitis were matched with a control child of identical sex and age. Parents were interviewed about environmental exposures inside the home. The authors concluded that wood-burning stoves were independently associated with a higher risk of respiratory infections (odds ratio [OR], 4.2; $P < 0.001$) (17). Robin and colleagues subsequently examined acute lower respiratory tract illness in Navajo children (18). Children with acute lower respiratory tract illness were matched with control subjects who had a health record at the same hospital and had never been hospitalized for acute lower respiratory tract illness (*n* = 45). Findings suggested that wood-burning stoves were associated with an increased risk of acute lower respiratory tract illness (OR, 5.0; 95% confidence interval [CI], 0.6–42.8), but differences were not statistically significant (18).

Because wood stoves are commonly used on the Navajo reservation, investigating the efficacy and effectiveness of Environmental Protection Agency (EPA)-certified woodstoves is necessary. Recently, Champion and colleagues compared the emission factors (EF) of EPA-certified stoves using four of the most common solid fuel sources used by Navajo families (19). Ponderosa pine, Utah juniper, Black Mesa (grade C) bituminous coal, and Fruitland (grades B and C) bituminous coal were tested (19). Controlled emission testing was conducted to determine mass emission factors and energy emission factors. Coal produced much higher emissions than wood, but the Black Mesa variety produced the highest mass emission factors and energy emission factors for $PM_{2.5}$, organic carbon, and carbon monoxide (19). However, ponderosa pine had the lowest mass emission factors and energy emission factors, with 50% lower $PM_{2.5}$ emissions than Utah juniper during the preburn phase, and was recommended over Utah juniper or coal by the research team for wood stove use (19). These findings suggest that newer, EPA-certified stoves in combination with fuel sources such as Utah juniper may reduce exposure to harmful indoor pollutants that contribute to asthma development.

This review did not identify any studies that were specific to the Navajo reservation

Table 2. Peer-reviewed studies meeting inclusion criteria examining environmental risks and adverse respiratory outcomes in Navajo and American Indian/Alaska Native children

Author(s)	Publication Date	Location	Methods	Environmental Concept	Specific to Navajo	Specific to AI/AN	Findings
Morris and colleagues (17)	1990	Conducted at the U.S. Public Health Service hospital clinic in Tuba City, AZ	Case–control study ($n = 58$); age- and sex-matched pairs ranging from ages 2 wk to 24 mo; cases = Navajo children with a diagnosis of bronchiolitis or pneumonia; control subjects = Navajo children who presented to the outpatient clinic for well-child care with no acute infectious disease	Wood stoves	X		Wood-burning stove use (OR, 4.2; 95% CI, 1.69–12.91) and respiratory illness exposure (OR, 3.7; 95% CI, 1.58–11.30) were associated with higher risk of lower respiratory tract infections
Robin and colleagues (18)	1996	Conducted at the U.S. Public Health Service Indian Hospital in Fort Defiance, AZ	Case–control study ($n = 45$); age- and sex-matched pairs ranging from ages 1 to 24 mo; cases = Navajo children hospitalized with an acute lower respiratory illness; control subjects = Navajo children who had a health record at the same hospital and had never been hospitalized for an acute lower respiratory illness	Wood stoves; cook stoves	X		Increased risk of ALRI for children living in households that cooked with any wood (OR, 5.0; 95% CI, 0.6–42.8), had indoor air concentrations of respirable particles $\geqslant 65\ \mu g/m^3$ (i.e., 90th percentile) (OR, 7.0; 95% CI, 0.9–56.9), and where the primary caretaker was other than the mother (OR, 9; 95% CI, 1.1–71.4)
Bunnell and colleagues (16)	2010	Conducted on the Navajo reservation in the Shiprock, NM area	Household exposure risk analysis ($n = 137$), analysis of hospital records ($n = 133{,}759$ records over a 6-yr period); ($n = 12$ air samples from 2 field sites); assessment of fine particulate matter concentrations ($n = 20$ indoor samples)	Wood stoves; coal combustion; outdoor air pollution	X		25% of stoves were not designed to burn coal; residents in the Shiprock area appear to be at greater risk for respiratory disease than nearby communities (annual asthma prevalence in Shiprock, NM = 16.762%); respiratory disease burden was increased in the winter compared with the summer, yet power plant emissions were greater in the summer than in the winter
Ward and colleagues (20)	2011	Conducted on the Nez Perce Reservation in northern Idaho	Pre- and postassessment of a wood-stove changeout program for new, EPA-certified wood stoves in homes ($n = 16$); indoor air quality samples were analyzed from each home	Wood stoves		X	The wood stove changeout/exchange program resulted in 10 homes that had improved indoor air quality (reduction in $PM_{2.5}$), 5 homes demonstrated unimproved or worsened $PM_{2.5}$ values, and 1 home was lost to follow-up. 52% reduction in indoor $PM_{2.5}$, and maximum spike values were reduced by 60%

(Continued)

Table 2. *(Continued)*

Author(s)	Publication Date	Location	Methods	Environmental Concept	Specific to Navajo	Specific to AI/AN	Findings
Noonan and colleagues (21)	2012	Conducted in Libby, MT	Pre- and postassessment wood-burning stove replacement program for EPA-certified wood burning stoves; $n = 1{,}100$; health impacts were measured using surveys from parents of school-aged children. Changes in air quality over 6 yr were measured using compliance air monitoring data from the Montana Department of Environmental Quality ($n = 1$ site)	Wood stoves; outdoor air pollution		X	Ambient $PM_{2.5}$ was 27.6% lower in the winters after wood stove changeout; 27.6% reduced odds of reported wheeze for a 5-$\mu g/m^3$ decrease in average winter $PM_{2.5}$; lower ambient $PM_{2.5}$ was associated with reduced odds for reported respiratory infections, including cold (25.4%), bronchitis (54.6%), influenza (52.3%), and throat infection (45.1%)
Ward and colleagues (22)	2015	Conducted in 2 locations: Fairbanks, AK and rural western Montana	Three-armed randomized placebo-controlled trial with 2 household-level interventions: wood stove changeouts and air filtration units ($n = 98$ homes)	Wood stoves		X	No significant reductions in $PM_{2.5}$ were observed in homes receiving the wood stove changeout. The air filtration strategy demonstrated a 69% reduction in indoor $PM_{2.5}$ concentrations and 75% reduction in the particle count concentration
Champion and colleagues (19)	2017	Conducted at the University of Colorado Emissions Standardization and Testing facility	Experimental design that used a standardized protocol to conduct controlled emission testing of 4 materials commonly burned in Navajo home stoves on the Navajo reservation: ponderosa pine, Utah juniper, Black Mesa (grade C) bituminous coal, and Fruitland (grades B & C) bituminous coal	Wood stoves; coal combustion	X		Coal produced much higher emissions as compared to wood, but the Black Mesa variety produced the highest mEF and eEF for $PM_{2.5}$, organic carbon, and carbon monoxide. However, ponderosa pine had lower mEF $PM_{2.5}$ (1.7 g/kg; SD, 0.7) than Utah juniper (3.1 g/kg; SD, 0.5), with approximately 50% lower $PM_{2.5}$ emissions during the preburn phase. Ponderosa pine was recommended for wood stove use over Utah juniper or coal
Reece and colleagues (29)	1996	Conducted at IHS Clinics	545 randomly selected charts were reviewed from 22 IHS clinics for documentation of smoking history in patients	Tobacco smoke exposure	X	X	73% of records did not document tobacco use status in patients; 9% documented a nonuser, and 18% documented a current user. Documentation varied by the area, ranging from no documentation in the Albuquerque, Navajo, and Phoenix areas to 51% in the Oklahoma area.

Definition of abbreviations: AI/AN = American Indian/Alaska Native; ALRI = acute lower respiratory tract illness; CI = confidence interval; eEF = energy emission factors; EPA = U.S. Environmental Protection Agency; IHS = Indian Health Services; mEF = mass emission factors; OR = odds ratio; $PM_{2.5}$ = particulate matter less than or equal to 2.5 μm in aerodynamic diameter; SD = standard deviation.

Table 3. Environmental exposures suspected of affecting asthma development and severity/exacerbation in children on the Navajo reservation

Indoor Exposures	Outdoor Exposures
Heating & cooking sources	Coal plants
Wood-burning stoves	NOx*
Coal-burning stoves	SOx
Other material–burning stoves	Dust: metals*
Open fires	Dust: PM other than indoor smoke*
Gas stoves: NO_2*	Diesel*
Personal smoking	
Commercial tobacco*	
Mountain tobacco	
Ceremonial	
Marijuana	
Allergens	
Dog/cat dander*	
Domestic birds*	
Cow and horse*	
Rodents*	
Other animals	
Cockroach*	
Other insects besides cockroach	
House dust mite*	
Fungi*	
Endotoxin*	
Dampness, mold*	

Definition of abbreviations: NOx = oxides of nitrogen; PM = particulate matter; SOx = oxides of sulfur.
*Strong evidence that this exposure affects asthma development and/or severity/exacerbations.

and the implementation of woodstove exchange programs; however, such programs have been evaluated in other AI/AN populations. Ward and colleagues evaluated the effectiveness of a wood stove exchange program on the Nez Perce Reservation (20). Indoor air samples (*n* = 16) were collected in homes at baseline and after intervention, and homeowners were asked to complete activity and wood-burning stove logs. After crude rates were compared, the data indicated a 36% reduction in mean indoor $PM_{2.5}$ when older stoves were replaced with newer EPA-certified wood stoves. However, 10 homes demonstrated improved air quality and 6 homes demonstrated reduced air quality after intervention (20). The authors explained that reduced air quality in these six homes most likely resulted from poor burning practices, such as drying wood on top of the stove, burning wet wood in the stove, or burning incense, thus outlining the importance of incorporating culturally appropriate education with stove exchange programs (20).

Noonan and colleagues also examined the impact of a community-wide woodstove replacement program in 1,110 homes near Libby, Montana (21). Ambient air quality and parent-reported childhood respiratory symptoms were prospectively measured. The woodstove exchange program resulted in a 27% reduction in outdoor ambient $PM_{2.5}$ during the winter months and a reduced odds of parent-reported wheeze in children (OR, 0.73; 95% CI, 0.55–0.97) (21). A third study conducted by Ward and colleagues used a three-armed randomized, placebo-controlled trial to examine the effectiveness of household-level interventions for improving indoor air quality (22). Ninety-eight homes with wood-burning stoves were randomized into one of three treatment groups: *1)* wood stove replacement, *2)* active air filtration unit, or *3)* placebo air filtration unit. Indoor $PM_{2.5}$ was prospectively measure over two consecutive winters. Findings suggested that the air filtration strategy demonstrated the greatest reduction in $PM_{2.5}$ (69% reduction) inside homes (22).

Indoor cooking. Although no research specific to the Navajo reservation was identified that investigated exposure to domestic pollution from cook stoves, given the limited availability of electricity on the Navajo reservation, it is suspected that many Navajo families rely on indoor wood stoves and open fires for cooking, especially during the winter. A meta-analysis of 25 studies found a significant association between indoor biomass exposure and acute respiratory infection in children (OR, 3.53; 95% CI, 1.94–6.43) (23), suggesting that indoor cook stoves disproportionately expose women and children to harmful pollutants because of their traditional roles of cooking in the home (23). In many cultures, infants and toddlers are exposed to harmful levels of air pollution when they are strapped to their mother's back during meal preparation (23, 24). The adverse health impacts of biomass smoke exposure have been well established but remain inadequately understood in the United States. Sood and colleagues demonstrated exposure to wood smoke was linked with gene promoter methylation and synergistically increased the risk of reduced lung function in cigarette smokers among a sample of women in New Mexico (25).

Tobacco smoke. Children exposed to secondhand smoke are at an increased risk for respiratory symptoms, impaired lung function, and lower respiratory illness, and cigarette smoke has been established as a leading risk factor of lung disease and increased asthma severity (26). Among AI/AN adults 18 years or older, commercial tobacco use was 38.9%, as compared with 16.8% of the general U.S. population (27, 28), which indicates a higher risk for tobacco smoke exposure among AI/AN children. The Navajo Nation Youth Risk Behavior Survey indicated that 11.4% of Navajo students in sixth, seventh, and eighth grades reported smoking cigarettes on 1 or more of the past 30 days, and 16.4% of students had smoked cigarettes or cigars in the past 30 days (*n* = 9,152 students) (4). Our review included the work of Reece, which indicated that clinical documentation of tobacco use in Navajo area IHS clinics was 0% (29). Recently, Nez-Henderson and colleagues found that male sex and younger age were associated with higher odds of cigarette smoking in a sample of southwestern American Indian tribal members (30). These recent data suggest that cigarette smoking may be on the rise among Navajo youth, but more research is necessary.

Indoor allergens. Allergic asthma is common among children, and exposure to indoor allergens (e.g., dust mite, cockroach, fungi, rodents, cats, dogs) may provoke asthma exacerbation (31, 32). Coexposures, such as endotoxin's role in allergic asthma and atopy, may also increase childhood asthma prevalence and severity (33). Padhi and colleagues found a significant association between biomass burning and increased indoor endotoxin levels (34), and the synergistic relationship between endotoxin and diesel exhaust has been associated with increased frequency of wheeze in children (35). Although the Navajo reservation is a semiarid region and dust-mite and fungal exposures are believed to be low, there is little research to support this notion. We found no literature regarding indoor exposures among Navajo or AI/AN children but propose this is an important area for future investigation.

Outdoor Exposures

Exposure to toxic air pollutants has been associated with increased incidence and severity of asthma, emergency department use, hospital admissions, and use of asthma medications (36). Since the 1960s, the Navajo reservation has experienced high levels of pollution from coal-fired energy production, mining operations, and blowing dust storms.

Coal-fired power plants. The long-range transport of fine particles found in coal-fired sulfur emissions has been associated with asthma morbidity, increased lower respiratory symptoms, and decreased peak flow (37). Only one study met our review criteria: Bunnell and colleagues completed a multicomponent study comparing the outdoor air quality to the indoor air quality in Navajo homes ($n = 20$) (16). The study was conducted near Shiprock, New Mexico where there were two coal-fired power plants nearby; however, industrial activities and motor vehicle use were limited. During the winter months, atmospheric thermal inversions often trapped air pollution low to the ground (16). Bunnell and colleagues demonstrated that the average indoor ambient $PM_{2.5}$ concentration was much greater than the average outdoor ambient $PM_{2.5}$ concentration ($36.0\ \mu g/m^3$ and $9.95\ \mu g/m^3$, respectively), and 9 of the 20 homes had levels far exceeding the EPA guidelines (16). When examining hospital admission and outpatient visit records ($n = 133{,}759$), the respiratory disease burden was much higher in the winter months than the summer months (16). Interestingly, the power plant emissions were much higher in the summer months, as a result of increased energy demands in the Southwestern United States, which was inversely correlated with the respiratory burden (16, 38). Bunnell and colleagues determined that coal burning inside Navajo homes was a primary risk factor for respiratory disease burden (16).

Diesel exhaust. Diesel exhaust has been associated with increased asthma and allergy symptoms, increased asthma exacerbation, and decreased lung function and has been implicated as a causative agent in lung cancer and respiratory disease (39). Approximately 50 to 94% of diesel particulate matter is classified as fine or ultrafine particulate matter. Diesel particulate matter is highly respirable, coats a large surface area of the lungs, and can easily reach the lower respiratory tract in children (39). Past studies have indicated that diesel particulate matter and $PM_{2.5}$ concentrations within the school bus microenvironment consistently exceed federal air quality standards and do not sufficiently protect children's health (40, 41). Among urban children living near roadways, diesel "soot" fraction $PM_{2.5}$ significantly contributed to PM exposure and was associated with pollution-related asthma exacerbation (42). Children with longer bus commutes are exposed to increased concentrations of diesel particulate matter, black carbon, and oxides of nitrogen (41, 43).

We found no literature examining diesel exposure among Navajo or AI/AN children; however, exposure to diesel exhaust and harmful pollutants remains a valid concern in Navajo communities. Many Navajo children travel long distances to school, and more than 83% of roads on the Navajo reservation remain unpaved (44). The Chinle Unified School District transports 4,200 students, and 60% of the roads in this district remain unpaved (45). Navajo children in Blanding, Utah spend 4.5 hours per day on the bus, and Monument Valley High School students spend more than 6 hours per day on the bus (46). Also concerning is the disproportionately high bus failure rate on the Navajo and Apache reservations, which range from 40% to 88%, compared with the statewide average of 21% (45). Chinle Unified School District had a 41% fail rate (45), and many failed inspections cited major exhaust leaks entering the school bus cabin (47).

Mining and dust. Exposure to metals (e.g., copper) has been associated with asthma symptoms and increased risk of asthma in school children (48). Heavy metals, such as iron, nickel, cadmium, and chromium, are associated with increased wheezing symptoms, and higher blood chromium levels have been associated with increased coughing episodes (49, 50). Chronic exposure to arsenic in drinking water has also been associated with respiratory complications (51). Historical uranium mining has also been a concern, as blowing dust from more than 1,200 abandoned uranium mines has been implicated in adverse health effects, which may include respiratory health (52). A recent study determined that dust storms in the United States are most prevalent in Arizona and southern California (53). Dust is an important consideration on the Navajo reservation, because overgrazed land and severe drought have promoted desertification and increased the frequency of desert dust storms and wildfires. Currently, mobile sand dunes cover over 30% of the Navajo reservation (54). Therefore, dust and desertification are unique environmental determinants that may influence respiratory disease in this population.

Discussion

In this review, we systematically searched for peer-reviewed articles but were unable to find a large body of evidence regarding pediatric asthma on the Navajo reservation. Therefore, we integrated literature regarding the environmental exposures (both indoor and outdoor) known to enhance the risk of asthma on the Navajo reservation. Among the environmental risks discussed in this review, the most abundant peer-reviewed literature specific to the Navajo reservation and respiratory illnesses was conducted on indoor air pollution, with an emphasis on exposure to wood-burning stoves and coal combustion. Although exchanging older stoves for newer stoves is one possible solution, the high cost of such interventions may not be feasible for this population. Using more practical and low-cost interventions for families with lower socioeconomic status is important. Community-based participatory research approaches that focus on promoting best burning practices (i.e., ensuring wood is aged and properly seasoned; burning woods that produce less smoke, burn slower, and provide more heat energy) are necessary. Traditional cooking methods (especially if commonly used within the indoor microenvironment) remain a potential area for intervention, considering the large number of Navajo homes that lack access to electricity.

Diesel exhaust exposure on the school bus is an important future direction for interventions. Exposure to diesel exhaust has deleterious effects on children's health, and protective measures include using newer and more efficient buses for the longest bus routes, limiting school bus idling to reduce exposure, and paving frequently used sections of dusty roads or other road infrastructure improvements.

We also sought literature on other known indoor asthma triggers, such as animal and pest allergens, mold, pollens, endotoxin and tobacco smoke exposure, and ceremonial smoke exposure, but no peer-reviewed literature specific to the Navajo reservation was available. Gaps in current research investigating indoor environmental allergens remain an important future direction for researchers, especially as they relate to increased asthma prevalence on the Navajo reservation. Quantifying ceremonial tobacco smoke and cigarette smoke exposure among the Navajo is important, but challenges exist with acquiring this information. Therefore, partnerships with the Navajo Nation and community-based participatory research methods are essential to obtaining accurate information while practicing cultural humility among this population.

Although our integrative review found a scarcity of published literature regarding the environmental factors influencing pediatric asthma in Navajo children, there is some evidence to suggest environmental risks may contribute to the disparate burden of asthma in children on the Navajo reservation. Some of these environmental risks, such as the common use of indoor heat and cook stoves, locale-specific indoor and outdoor allergens and fungi, various forms of personal smoke exposure, and diesel exhaust, are well known and are modifiable. Other potential risk factors such as dust storms, dust from contaminated soil, and coal-fired power plants are less recognized, yet may present additional insidious risks. The lack of published research affects our ability to adequately understand the causes of asthma disparities and plan future interventions.

The historic mistreatment, trauma, environmental injustices, and contraventions against American Indian/Alaska Native people by the U.S. government have led to a general mistrust of research. Some researchers have perpetuated this mistrust by publishing research that used culturally insensitive methods, was not collaborative with local partners, and fundamentally failed to understand the problems and resources of the Tribe. Furthermore, these publications often stigmatized and stereotyped American Indian/Alaska Native people. American Indians and Alaska Natives have experienced poor health outcomes for more than 500 years, and political and economic influences have continually affected the response (55). Such disparities are often viewed as markers of social injustice that clearly parallel disparities in wealth and power (55). Therefore, the Navajo Nation has been a leader in the movement by tribes to assert sovereignty in research conducted on the Navajo Nation, who mandate by law a specific process for conducting research on the reservation.

Future priorities to address children's asthma, therefore, should be built through sustainable collaboration, including: addressing indoor air pollution from wood-burning stoves and coal combustion, diesel exhaust exposure from long bus rides, and understanding the burden of indoor allergens such as animal dander, dust, molds, pollens, and other known triggers of asthma exacerbation. Such future research could inform policy regarding effective ways to improve asthma disparities and be broadly applied to other Tribal reservations and rural populations with similar environmental risk factors. These indoor and outdoor pollutant exposures require further, careful investigation to fully describe and understand their impact on pediatric asthma for the Navajo Nation's children. Ultimately, this information can direct comprehensive interventions to improve outcomes for children with asthma. ■

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Air Monitor P570

A Cultural, Spiritual and Health Impact Assessment

Of Oil Drilling Operations in the Navajo Nation area of
Counselor, Torreon and Ojo Encino Chapters

January 15, 2020

Prepared by the Counselor Health Impact Assessment - Hozhogo'na'ada Committee

CA
Ex. 32

Counselor Health Impact Assessment (HIA) - Hozhogo'na'ada (HNDA) Committee

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Bridging the Cultural, Spiritual and Health Impacts of Oil Drilling

David Tsosie, Ed.D.

The Holy Surface Earth People (Diné) have always tried to follow the many traditional teachings that have been shared with them by the Holy People since time immemorial. These teachings have been passed down from one generation to another and have for centuries established the parameters for the relationship that has been maintained by the Diné people. Our elders tell about the stories of the creation when the Holy People came into the White World/Glittering World. They placed the sacred mountains, the rivers, the plants, the animals, the birds, and all life forms in their proper places and environment. They ordained, through songs and prayers, the earth and universe to embody Nitsahakees (thinking), the water and the sacred mountains to embody Nahata (planning), the air and vegetation to embody Iina' (life), the fire, light, and offering sites of variegated sacred stones to embody Sihasin (wisdom). These became the fundamental tenets established to follow an order of thinking, being the foundation of planning, and life, being the foundation of wisdom. These tenets became an integral part of our life pattern where all important events have first to be thought out, then planned, then they all become part of life process, and from here, wisdom is attained to guide the future generation.

More importantly, the Diné Traditional Law mandates that the teachers of traditional laws, values and principles must be respected and honored if the people and the government are to persevere and thrive and that their participation and contributions of the traditional values and principles of Diné life way will ensure growth of the Navajo Nation. Additionally, the Diné Natural Law emphasizes that:

1. The four sacred elements of life, air, light/fire, water and earth/pollen in all forms must be respected, honored and protected for they sustain life;
2. All creation, from Mother Earth and Father Sky to the animals, those who live in water, those who fly, and plant life have their own laws and rights to exist; and
3. We, the Diné, have a sacred obligation and duty to respect, preserve and protect all that was provided for us and that we were designated as the steward of these relatives and must acknowledge them thorough our use of the sacred gifts of language and thinking.

It is important to note that Mother Earth and Father Sky are part of us as Diné and we are part of Mother Earth and Father Sky; thus, we must treat this sacred bond with love and respect without exerting dominance. The love, respect and honor that is shown to our natural environment is displayed by following the proper protocols of making offerings at sacred sites requesting permission to only take what is needed and to place them back with prayers and songs.

There are ceremonial stories of how many of these elements were placed into the earth and sky to be part of the cosmic order. If they were excessively removed, there would be devastating consequences. One story tells of the destruction of the monsters and evil forces that came upon the people after they came into the Glittering World. Monster Slayer and Born for the Water brought about the destruction of all the evil forces/energies that were annihilating the people living in the Glittering World. After all of these evil forces were destroyed, they were placed into the earth and sky and it was declared that they should never be disturbed.

After the obliteration of the evil forces, the people lived in a peaceful environment for a long time. One day some of the people noticed a change in the environment and called on the Holy People for guidance. The Holy People discussed the situation and asked the Early Twilight Dawn deity to assist in correcting the disharmony that had come into the environment. To restore order and harmony, the Twilight Dawn deity gathered all of the sacred mineral people at Dziil Na oodilii (El Huerfano). After much discussion, it was decided to send all of the mineral people into the earth to restore order and become caretakers. It was then agreed among the Holy People that minerals can only be taken out of the earth with prayers, songs, and offerings. After their use, minerals will be placed back into the earth with prayers, songs and offerings. There would be devastating consequences if large quantities of minerals were taken out of the earth without following the proper protocols.

We have seen these devastating effects in how they have brought certain health complications and illness like cancer, respiratory problems, and other sicknesses among our people.
Under the leadership of the late Dr. Larry Emerson, a study titled Hazho Nadaii was started to examine problems and issues through a Diné Lens, meaning looking at problems and issues by incorporating Diné traditional stories and teachings to address how some of these complications could be dealt with. It was through this initiative that the Counselor Health Impact Assessment – Hozhogo'na'da Committee started looking at the concerns of communities around oil drilling activities and the use of fracking to acquire more oil. We undertook a two-phase approach to looking at the problem oil drilling operation in the three Chapters of Counselor, Torreon, and Ojo Encino (the Tri-Chapter).

Since 2015, the residents of Counselor Chapter have voiced concerns about sudden and unusual health symptoms experienced from breathing polluted air around oil wells near their homes and roads. The Chapter communicated those concerns in a 2015 Resolution to the Navajo Tribal Council and requested a Health Impact Assessment (HIA) be conducted before further oil operations were permitted. In January 2018, the Navajo Nation Human Research Board approved a two-part Health Impact Assessment: Part One - to conduct air sampling and voluntary health surveys in Counselor Chapter, and Part Two – Hozhogo'na'ada - the continuation of Hazho Nadaii – a traditional survey taken by residents from Counselor and two neighboring chapters, Ojo Encino and Torreon.

The first phase of the Health Impact Assessment (HIA) examines the changes that intensive oil drilling has made to the air quality of Counselor Chapter, and identifies related health symptoms reported by chapter residents.
The second phase of the Assessment, Hozhogo'na'ada (HNDA) is a survey tool and model that seeks to identify degrees of concern felt by the individual regarding the familial, community, cultural, and environmental impacts from current oil drilling and the threat of expanded land leasing facing these three Diné communities.

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Part 1: HIA – Health Impact Assessment - Counselor Chapter

Part 2: HNDA – Hozhogoo'na'ada - Counselor, Ojo Encino, Torreon Chapters

I. Introduction - Is the Open Air Safe?

Counselor Chapter is a rural, sparsely populated, high desert area, with tree-covered mesas and pinion-juniper forests and grasslands. There are an estimated 700 residents and many live in small familial clusters in the Cross Roads and Cornfields areas in the central area of the Chapter. The Chapter House, Lybrook Community School, and the Lybrook Ministries are located on the Chapter's northern boundary of US Highway 550, approximately 35 miles north of Cuba. The northern half of the 70,771-acre chapter is a heavily developed gas and oil area with more than 400 oil wells, industrial wastewater ponds, storage tanks, pipeline infrastructure, and a network of dirt access roads for oil company workers across the community.

For over five years, Counselor leaders and residents have reported their concerns to tribal, state and federal agencies and taken actions to identify the multiple impacts of this industrial development within the community. A young father-to-be spoke at a Chapter meeting on May 23, 2016 with these words: "How is our younger generation going to survive? Is the open air going to be safe? Will it cause birth defects or not?" This report attempts to answer these questions and many others, and to reveal how little is yet known about oil development's ultimate impacts on human health and the environment.

Points to bear in mind regarding local impacts of well emissions:

- Emissions from over 400 gas and oil drilling sites in Counselor Chapter are significantly increasing the reported respiratory health symptoms of residents that mirrors results of national health studies.
- Continued and cumulative exposure to elevated levels of toxic gases, particularly formaldehyde, from nearby well operations can lead to chronic respiratory effects and cancer[1].
- Lease sales for oil development are proposed in the adjacent chapters of Torreon and Ojo Encino raising concerns that similar health, safety and cultural impacts will be felt in those communities.
- Exposures to emissions do not occur evenly over time, but spike in intensity periodically.
- The extent to which people are exposed to toxins is determined by the concentrations of emissions vented and leaked, combined with weather conditions.
- There is now an abundance of information about shale gas and oil site emissions and their potential to do harm to the health of residents who live within 5 miles of well operations, but almost no data on the Checkerboard Area of the Navajo Nation.

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[1] Southwest Pennsylvania Environmental Health Project Report: "Counselor Chapter Air Quality Assessment Results: Particulate Matter (PM2.5) and Volatile Organic Compounds (VOCs)", August 3, 2018

Getting Started: Health Impact Assessment Checklist

Free, Prior and Informed Consent: Have Counselor residents been provided the information they need by state, tribal or federal agencies before leasing their land for gas and oil development?

	NOT PROVIDED	INCOMPLETELY ADDRESSED	ADDRESSED WELL
Attention to concerns of residents		X BLM-BIA meetings w/ no explanation of potential harms or permanent effects	
Listing of chemicals emitted and at what concentrations	X Not Provided		
How often will emissions occur and at what times of day	X Not Provided		
Projected exposure within a mile of site – daytime and nighttime at peak level	X Not Provided		
Radioactive material present	X Not Provided		
Air monitoring plan specified			X Counselor HIA Monitoring Project w/ EHP
Warning system in place for times of planned or unplanned high releases for those within a mile	X WPX explosion and 5 day fire (July 2016) is one of many examples of need for evacuation plan/response		
Blowdown emissions addressed	X Not Provided		
Emissions from flares estimated	X Not Provided		
Sufficient distance from schools, day cares and other sensitive locations	X Lybrook School has 31+ wells located within 2 miles of the property		
HEALTH IMPACTS			
Chronic and episodic exposure effects on children addressed	X Not Provided		
Exposure effects on fetal development addressed	X Not Provided		
Effects of PM2.5 addressed			X Counselor HIA monitoring w/ EHP analysis
Effects of VOCs addressed			X Counselor HIA Monitoring w/ EHP analysis

QUESTIONS OFFICIALS OUGHT TO ANSWER BEFORE GOING FORWARD WITH SHALE GAS OR OIL DECISIONS IN NEW MEXICO

Public agencies - Bureau of Land Management (BLM), Bureau of Indian Affairs (BIA), Navajo Nation EPA, NM Energy, Minerals & Natural Resources Department – at the federal, tribal, and state level – should address the health concerns raised in this report and establish Conditions of Approval or prohibit certain industrial operations in inhabited areas to protect the public from harm. In order to protect public health, it is necessary to know whether dangerous levels in pollutants will occur in a developing area and what health effects may occur in the short or long-term.

This Health Impact Assessment helps organize information needed to start answering critical questions:

1) What chemicals are being emitted or leaked? 2) Are people being exposed to harmful levels of emissions? 3) What is the local air quality? 4) What health effects from chemical exposures have been determined? 5) How can your agency mitigate or remove existing or potential harms?

II. Chemical Exposure in Counselor

The complete list of chemicals being used in oil drilling operations in Counselor is unknown. Of the 75 toxic substances tested for in four 24-hour samples, a total of 8 toxic chemicals were detected. Results (Appendix 2) found formaldehyde at 4 sites, at elevated levels (greater than 0.003 ppm) that carry recommended actions to reduce exposure for local residents. Other detected chemicals:

2-Propanol
Acetone
Chloromethane
Dichlorodifluoromethane
Hexane
Methylene chloride
Trichloroethene

Certain classes of particles and chemical agents have well known health effects that have been documented by the Occupational Safety and Health Administration (OSHA), American Cancer Society, Agency for Toxic Substances & Disease Registry (ATSDR) and in scientific journals, medical reports, clinical studies and media articles[2].

The presence of these chemicals makes it likely that other commonly used chemicals at well sites are present at different stages of operations.

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[2] "Compendium of Scientific, Medical, and Media Findings Demonstrating Risks and Harms of Fracking" (5th Ed., 2017) Physicians for Social Responsibility, Concerned Health Professionals of NY.

Chemicals Detected, Methods of Exposure and Associated Symptoms

2-Propanol – Inhalation; exposure can cause headache, dizziness, nausea, respiratory depression and coma. (Highly flammable)
https://www.google.com/search?source=hp&ei=qw49XKyHKo2_jgT7kIf4Bw&q=2-propanol+hazards&oq=2-&gs_l

Acetone – Inhalation; exposure can irritate eyes, nose and throat, and cause dry, red, cracked skin. (Highly flammable) https://www.ccohs.ca/oshanswers/chemicals/chem_profiles/acetone.html

Chloromethane & Dichlorofluoromethane – Skin contact: exposure can cause severe irritation and chemical burns to eyes.
https://www.msdsonline.com/2015/02/20/dichloromethane-methylene-chloride-hazards-safety-information/

Hexane – Inhalation: short-term exposure affects the nervous system and causes headaches, dizziness and nausea. Chronic exposure can lead to severe damage to the nervous system, dermatitis and irritation of the eyes and throat. (Solvent)
https://www.msdsonline.com/2014/11/19/understanding-the-hazards-of-hexane/

Methylene chloride – Inhalation and Skin contact: exposure may cause mental confusion, dizziness, nausea, and headache. Continued exposure can cause eye and respiratory irritation. Skin contact may cause irritation or chemical burns. (Solvent)
https://www.osha.gov/Publications/osha3144.html

Trichloroethylene (TCE) – BANNED in food and pharmaceutical industry since 1980s - Skin contact: exposure may cause fetal toxicity and causes effects on the nervous system related to hearing, seeing, balance and heartbeat, also liver and kidney damage. (Non-flammable)
https://www.edf.org/health/banning-high-risk-uses-trichloroethylene-tce

Formaldehyde – Inhalation: exposure can cause cough, sore throat, nosebleeds and eye irritation. It can cause cancer of the nose and throat and is harmful for people with asthma, bronchitis or other breathing conditions.
https://www.cancer.org/cancer/cancer-causes/formaldehyde.html

Facilities of Concern

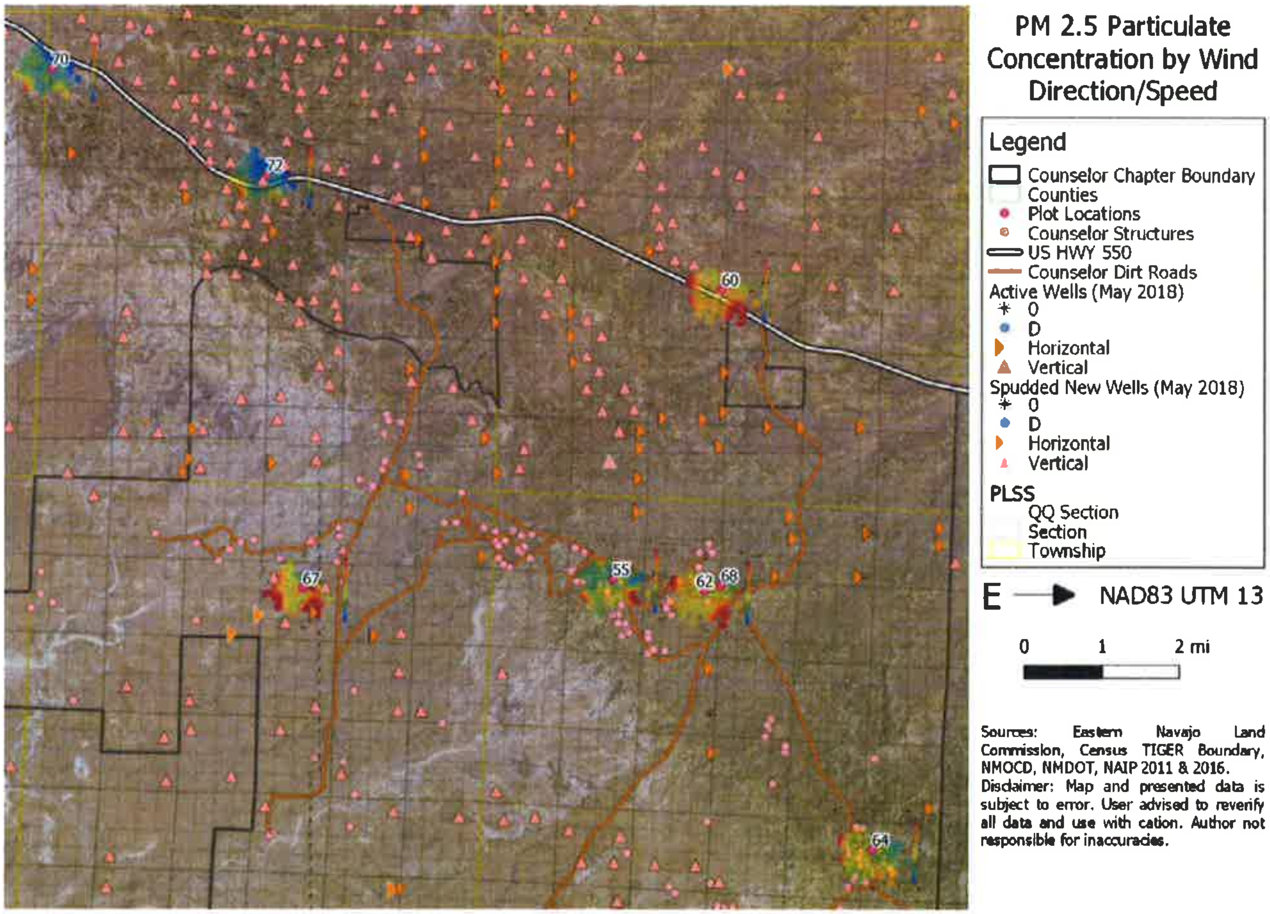
Gas & Oil Wells & Pipelines (Components & Maintenance using solvents and flammables):

- Tanks, pipelines, equipment and other quantifiable descriptions of pollution sources on well pads, including amount of gas moved through pipelines, type of engines, horsepower of engines, pipeline pressure, diameter of pipeline, and any safety procedures followed: **Not described to public**
- Mobile tankers and wastewater on site that have potential to contaminate area: **Not described to public**

Table 1. Counselor Land Use within ½ mile to 1-mile radius of gas and oil wells

Parcel Category	1/2 Mile Radius	1 Mile Radius
Grazing Land	X	
Residential	X	
Health Clinic	X	
Public Water well		X
Church	X	
Ministry complex	X	
Oil Refinery	X	

Setbacks



Sources: Eastern Navajo Land Commission, Census TIGER Boundary, NMOCD, NMDOT, NAIP 2011 & 2016. Disclaimer: Map and presented data is subject to error. User advised to reverify all data and use with cation. Author not responsible for inaccuracies.

Figure 1: Map of Structures in Counselor NM showing oil wells and 8 air monitor sites

Gas and oil wells are in close proximity to residences and other structures in the areas leased for development. There is no fixed setback distance from well pad to residential structure, school, or business. Setbacks vary from 330 feet (or less if the well is an older vertical well) to 660 feet. The majority of the 700 residents in Counselor live within 1 mile of one or more wells, pipelines, and/or other gas and oil infrastructure. Colorado now requires a 1000′ setback while medical professionals have estimated that a "diluted dose" of continuous emissions is attained with a residential setback of 6,600′[3] from large well sites, compressor stations, storage areas or processing plants.


Photo by Teresa Seamster

Figure 2: Partially developed area near Heart Mesa (near Cross Roads) leased for future oil drilling.

Residents are concerned about drilling on lands within the chapter that have not been developed before. New pollution sources have significant cumulative impacts on residents. Additional gas and oil wells will add to whatever air pollution is already present. Each permit to drill additional wells should be evaluated by what it *adds* to current impacts on local air quality, not only what emissions it produces itself.

New Mexico Gas and Oil Emissions Inventory show High NOx and S2O Levels

A national oil and gas inventory by ENVIRON for 2018 was estimated by growing the 2002 inventory using factors derived from resource management plans produced by the Bureau of Land Management and regional forecasts made by the Energy Information Administration. Methodologies were developed that could be applied consistently across the western region, without overlooking the variability in local production characteristics, control requirements and inventory thresholds. Application of these methodologies resulted in the addition of almost 120,000 tons of NOx emissions to the 2002 Western Regional Air Partnership (WRAP) emission inventory. New spatial surrogates were generated based on well locations to appropriately distribute these emissions.

Additional effort was made to estimate emissions in new development areas without base year emissions. The resulting approach incorporated the most complete information available on the anticipated oil and gas development in the western US region to produce an inventory that predicts a doubling of non-point oil and gas NOx emissions between 2002 and 2018. Emissions for each formation were calculated as the product of the formation specific emission factor and the number of wells drilled in the formation in 2002. The emissions for that formation were then allocated to the

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[3] www.environmentalhealthproject.org (Recommendations for Mitigation of UOGD to Protect Public Health)

counties that intersected the formation based on the fraction of the wells drilled that were drilled in each county's portion of the formation.

The state total drill rig NOx and SO2 emissions that resulted from this procedure are shown in Table 2. The adjustments made to the emission factors are apparent in these results. While significantly more wells were drilled in the State of Wyoming than in New Mexico, the emissions in New Mexico are higher than in Wyoming. This occurs because many of the Wyoming wells were drilled quickly and to a shallow depth, as commonly occurs for the Powder River Basin CBM wells. In contrast, the wells in New Mexico were, on average, drilled deeper and took longer to drill. (See Western Regional Air Partnership Technical Support System https://views.cira.colostate.edu/tss/Results/Emissions.aspx).

Table 2. State total drill rig emissions.

State	**Wells Drilled**	**NOx (tons)**	**SO2 (tons)**
New Mexico	932	6,645	1,444
Total in US:	*6,088*	*21,536*	*3,706*

New Mexico has drilled slightly > than 15% of the total US rigs and generates > 30% of the Nitrogen Oxide emissions and almost 39% of the Sulfur Dioxide emissions for the US.

Sulfur Dioxide (SO2): Levels of this emission are not routinely reported to the public or highlighted as a health risk in publicly available county air quality or health statistics. At high concentrations SO2 can cause life-threatening accumulation of fluid in the lungs (pulmonary edema). Symptoms caused by lower concentrations may include coughing, shortness of breath, difficult breathing and tightness in the chest. A single exposure to a high concentration can cause a long-lasting condition like asthma.[4]

III. Harmful Emissions

Current Regional Air Quality

2018 American Lung Association AQI Report:
San Juan County – High Ozone Days: Grade C
San Juan County – Particulate Matter Pollution: INC (incomplete state monitoring for PM)
San Juan County - Groups at risk (Lung Cancer, COPD, Asthma, etc)

Navajo Nation Environmental Protection Agency (NNEPA) Air Quality Control Program conducted air monitoring of measured criteria air pollutant levels in Counselor from April 14, 2016 to May 18, 2017. Data were downloaded monthly and quality checks (QC) done on the gaseous analyzers and particulate sampler. The observed 1-hour NO_2 and SO_2 did not exceed primary NAAQS; observed 8-

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[4] See EPA Integrated Risk Information System: https://www.epa.gov/so2-pollution/sulfur-dioxide-basics#effects

hour maximum O_2 and daily 24-hr. PM_{10} did not exceed NAAQS, with generally good to moderate readings. (See Appendix 3) Note: No comparisons were made with other locations in the chapter nor were monitoring distances from active wells reported.

Average and High Periods of Exposure in Counselor

Many of the chemicals released at gas and oil wells can have respiratory effects and increase asthma rates for adults and children. Some chemicals emitted can affect reproduction and infant mortality and disabilities. The National Environmental Pubic Health Tracking Network: (https://www.cdc.gov/nceh/tracking/).

Exposures from gas and oil wells are not constant. There are several variable contributors to individual exposure:

1) Emissions at any given time – There will be more emissions during a time when a large amount of gas is being vented or going through the pipeline as compared to when little or no gas is.
2) Content of the emissions – The content of the emissions also varies by the area of shale that the gas was released from. For instance, some gas may have more Hydrogen Sulfide than others; other sources may have more Radon or Radium.
3) Weather conditions – The weather (temperature, wind, and cloud cover) will affect whether a well's emissions will disperse quickly away or whether it will stay in close proximity.
4) Topography – The topography will affect how much emissions exposure a home might receive. Counselor has many mesas and arroyo areas that can either block air currents from home sites or trap air contaminants around residences for periods of time. Large flat open areas predominate the area and strong winds can quickly carry toxins from well sites to occupied structures before they have a chance to rise or mix with the air to become less hazardous. Some of the most polluted air has been found in these open areas.

Photo by Teresa Seamster

Figure 3: Winter flaring (2018) near Corn Fields residential area in Counselor

Exposures vary over time; even varying from one half-hour to the next. If you average the exposure level over the year or month or day, you will miss the high (and more dangerous) periods of exposure. For instance, over a **24-hour period the average particulate exposure was 29 ug/m3** but there was a period just before dawn that was **398 ug/m3** that was high enough to cause an asthma attack.

IV. Counselor Chapter Air Monitoring Results (2018)

The Counselor HIA Committee, under the guidance of the Environmental Health Project (EHP), conducted community air quality monitoring in the spring of 2018. Data were collected from eight indoor and outdoor residential and public locations in Counselor from mid-April to the end of May. These results have been compared to other results that EHP has reviewed in communities near shale gas and oil operations in New York, Ohio, California and Pennsylvania. (Note: Indoor results were reported to the residents living at the 8 locations and are not part of this community report.)

Outdoor Speck monitors were deployed during the week of April 8 to April 15 and were located an average of 30′ to 50′ away from the side of the house closest to the nearest oil well. All monitors were retrieved between 32 to 45 days later and sent to the Environmental Health Project in New Haven, Connecticut, for data analysis.

The analysis found that large-scale changes (peaks) in air quality averaged 2-4 peaks per day and lasted from 21-28 minutes per peak exposure. The time between peaks varied from 6 to 13 hours while the median for other communities sampled by EHP is 8.5 hours. The level of particles generally found outside between peak times was considerably higher in six locations compared to the median found in other communities, and the total sum of accumulated particle counts over the 32-day period was at or above average levels of accumulated fine particulate matter ($PM_{2.5}$) in other sampled communities nationally. With higher than average $PM_{2.5}$ levels, residents living near a source of air pollution are at greater risk for developing or worsening respiratory or cardiovascular diseases. Further, some air contaminants cause neurological effects or are carcinogenic.

Outdoor PM 2.5 Results from 8 Counselor Residential sites

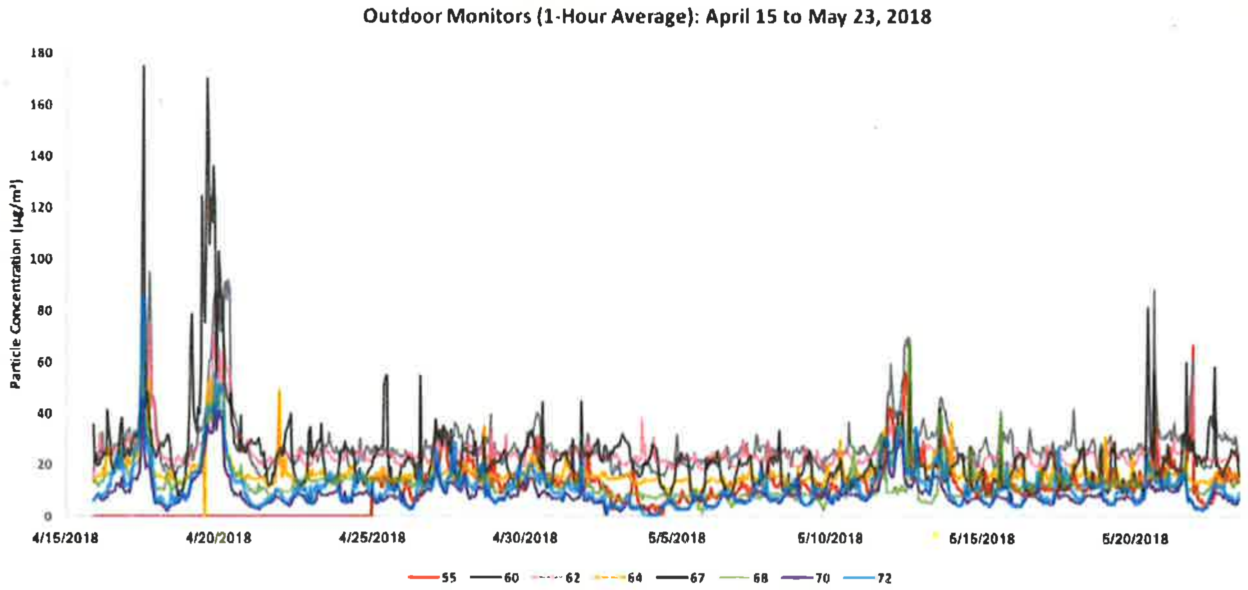


Figure 4: $PM_{2.5}$ Results from 32-Day monitoring period. Monitor numbers correlate to colors.

Figure 4 shows the results from eight outdoor Speck monitors placed in the community for 32 days. Significantly, there were many times when peaks in $PM_{2.5}$ (particulate matter in the air that are 2.5 microns in size) exposure occurred simultaneously at various locations, most notably on April 17, 2018 and April 19, 2018. When a source of air pollution is nearby, these conditions could cause increased exposure for residents. Chemicals from the source may combine with the particulate matter and travel to the deep regions of the lungs to cause respiratory problems or gain access to other parts of the body through blood-gas exchange.

Additional Outdoor Air Testing in Counselor

Volatile Organic Compounds (VOCs) samples were also collected at four of the eight Speck monitor sites. Sampling was conducted from May 29 to May 30, 2018 for a 24-hour period using four summa canisters and four sets of Radiello absorbing cartridges (hydrogen sulfide) and formaldehyde badges. The samples were tested for 75 chemicals. Three VOCs were detected on May 23, 2018 and seven on May 30, 2018. No Hydrogen Sulfide was detected but Formaldehyde was found at all locations. For all other chemicals identified there is a threshold to consider action. In this one sample, all chemicals were found at levels below what would cause immediate health concerns except Formaldehyde.

There are some 600 chemicals that can be used in the production of gas and oil, and sites can use different types of chemicals and combinations. However, there are several common pollutants such as VOCs, $PM_{2.5}$, and formaldehyde. EHP uses these 3 as "indicators" because scientists have measured and estimated the amounts of these chemicals emitted from oil/gas well sources. If these indicators are present in air samples, it is likely that other chemicals of concern are present.

Table 3: Elevated levels of Formaldehyde were found at all four locations

May 23, 2018	May 30, 2018
Acetone	2-Propanol
Chloromethane	Acetone
Dichlorodifluoromethane	Chloromethane
	Dichlorodifluoromethane
	Hexane
	Methylene chloride
All PEL- permissible exposure limits	Trichloroethene
	All PEL
Formaldehyde*	Formaldehyde*
0.0090 ppm	0.0070 - 0.0097 ppm
Take action at 0.003 ppm	Take action at 0.003 ppm

Previous Air Quality Testing in Counselor at Operational Well Sites

October 14, 2016
Two samples were collected at entrances to active wells along US 550 in Counselor and both showed levels of Toluene ((19µg/m3 and 72 µg/m3). These levels are under relevant health-based standards (acute 8 hour chronic reference exposure level) however **these levels of Toluene are unusually high**.

A 2013 survey of air quality in more than 100 locations nationally found daily "mean concentrations" of Toluene lower than in Counselor ranging from 0.073 - 19µg/m3.

April 18, 2017
Three air samples were collected at entrances to active wells along US 550 at 1) mile marker 100 north of Lybrook School; 2) at mile marker 107.5 south of the San Juan and Rio Arriba County line; and 3) at the intersection of US 550 and County Road 7900. Hydrogen sulfide was detected at mile marker 100 closest to the Lybrook School at a level of **7.6µg/m3**. (See ALS Lab results in Appendix 1)

Hydrogen sulfide is a gas that has a potently offensive odor of rotten eggs and exposure to it is associated with an elevated incidence of respiratory infections, eye and nose irritation, coughing, breathlessness, nausea, headache, and mental symptoms including depression. The US EPA reference concentration level (RL) is **2µg/m3.**

The level detected exceeded the RL but was below the Office of Environmental Human Health (OEHHA) California chronic reference level for hydrogen sulfide. **But if levels of 7.6µg/m3 generally are reached then these levels can pose a human health risk for students and staff at Lybrook School**. (Additional analysis from Mark Cherniak, Ph.D., Staff Scientist, Environmental Law Alliance Worldwide)

EHP Analysis of Counselor Air Monitoring Results

After air-monitoring results were obtained, the Counselor HIA Committee consulted with Environmental Health Project specialists: Celia Lewis, Ph.D., and Sujit Joginpally, M.D.

1. How does Counselor compare with other communities being monitored by EHP?

Six (6) out of the eight (8) monitored locations in Counselor Chapter recorded levels between 10 to 25 micrograms/meter^3, with only 2 locations reading at Baseline PM2.5 levels in other communities are generally below 10 micrograms/meter^3. the lower average PM2.5 level. Also, the total particle count over the 32-day monitoring period was at or above average levels of accumulated PM2.5 for other states.

2. Are Counselor's PM2.5 levels considered high?

Yes, because they are higher than average PM2.5 levels recorded at similar distances from oil wells in communities in New York, Ohio, California and Pennsylvania. Counselor is the first community in a southwestern state to be monitored by the Environmental Health Project.

3. What are some reasons for Counselor's higher levels of PM 2.5 and Formaldehyde?

Many homes in Counselor are located closer than a mile to one or more operating oil and gas wells. The recommended setback distance between occupied structures and wells is now 6600', or 1¼ mile. Many homes are "downwind" of wells that emit Volatile Organic Compounds (VOCs) and Formaldehyde (which can be formed from methane emissions in the presence of sunlight). Counselor has areas of open plains with numerous homes situated where the wind tends to blow towards the houses from a nearby pollution source. On sunny days with no wind, pollutants will rise quickly upward away from houses. On cloudy days with no wind, pollutants more slowly and mix with the air very slowly keeping emissions closer to the ground and more hazardous for residents. On windy days, pollutants from nearby wells can reach downwind homes nearby before chemicals can disperse.

Photo by Samuel Sage

Figure 5: Summa Canister monitoring Volatile Organic Chemicals (VOCs) at Counselor Chapter House in May 2018.

(See Appendix 2 for complete report: SWPA Environmental Health Project: Counselor Chapter)

EHP analyzed results for PM2.5 at eight residences/locations in the Counselor area. In the bar charts below, each blue dot represents the average results for outdoor air levels at one home. The red bar marks the average (median) of all results compiled by EHP outside New Mexico.

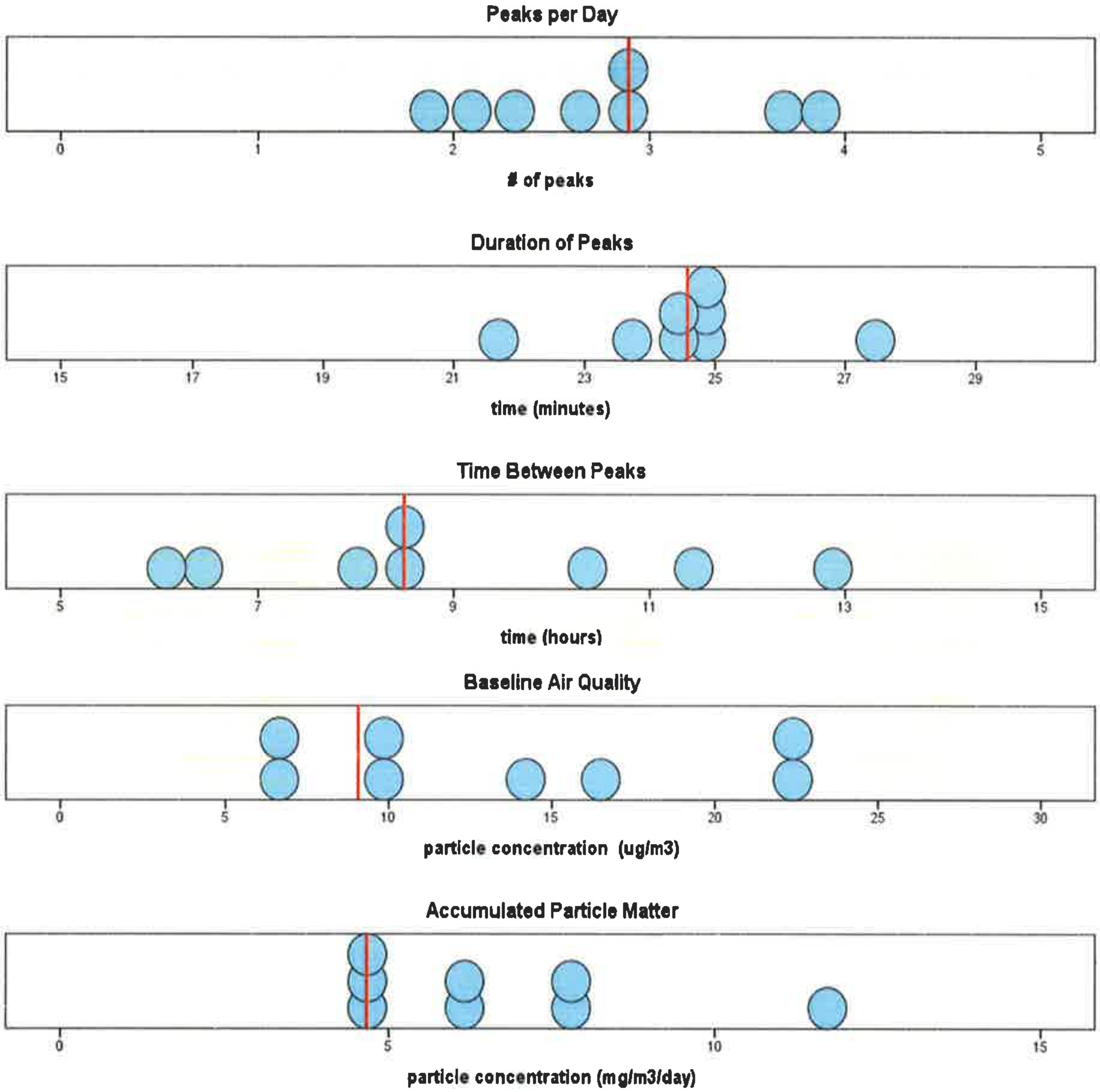


Figure 6: The range of results of $PM_{2.5}$ monitoring for five components measured Peaks per day, Duration of peaks, Time between peaks, Baseline air quality and Accumulated particle matter using Speck monitor data.

The results are shown in relation to the national data reviewed to date by EHP. The majority of locations in Counselor had higher particle concentration (ug/m^3) in their Baseline Air Quality and higher Accumulated Particle Matter (mg/m^3/day) than in similar locations monitored in other states.

Comparisons of Wind Speed and Direction on Individual Site Air Pollution

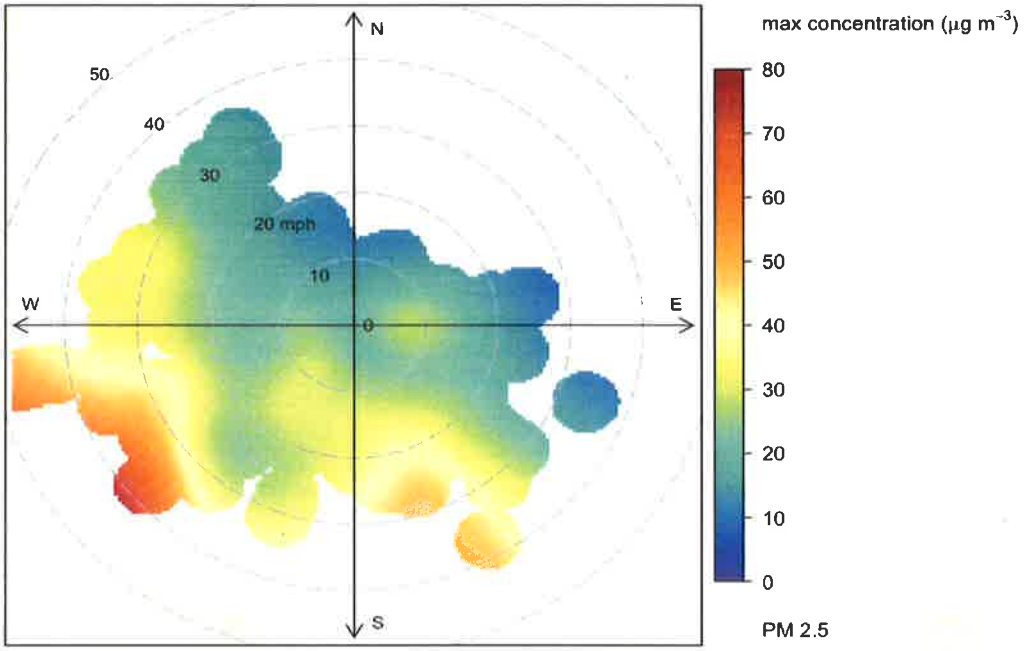


Figure 7: Counselor East (CE1) P568

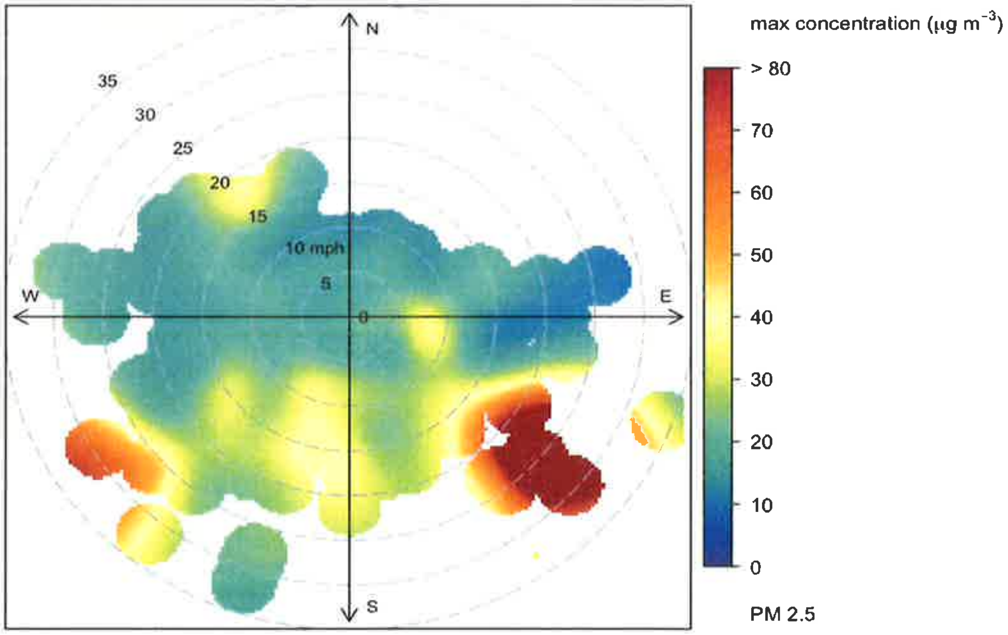


Figure 8: Counselor East (CE3) P555

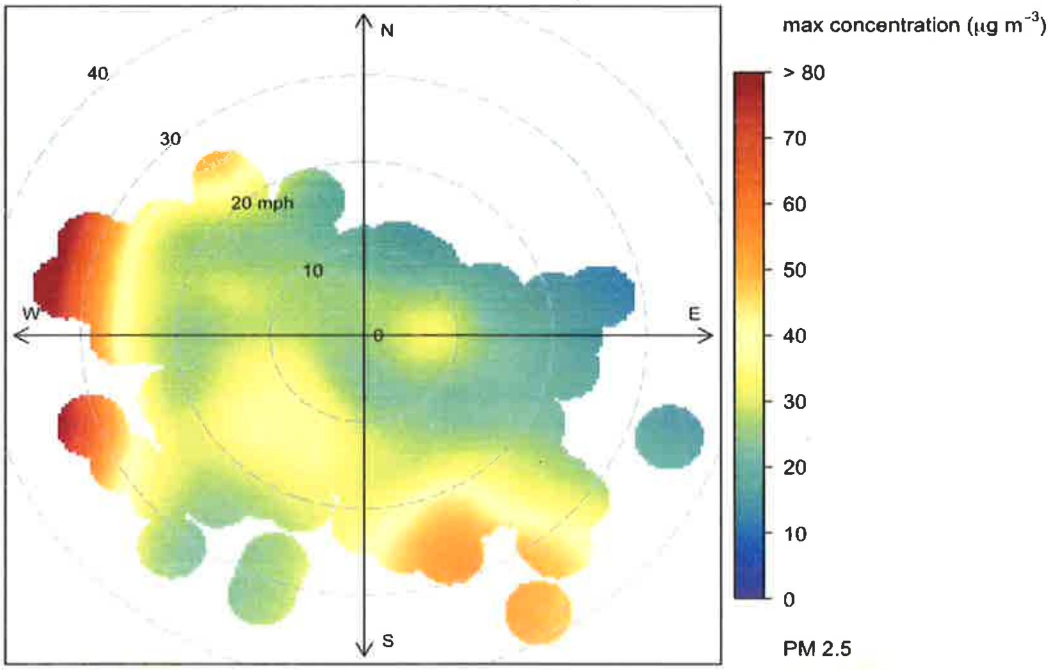


Figure 9: Counselor East (CE4) P564

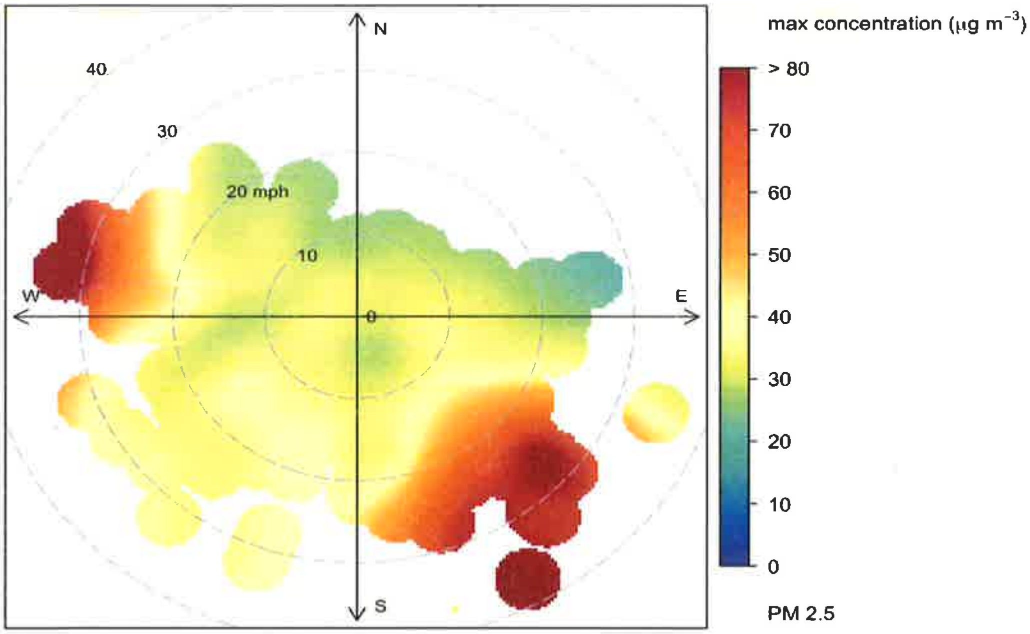


Figure 10: Counselor East (SE8) P562

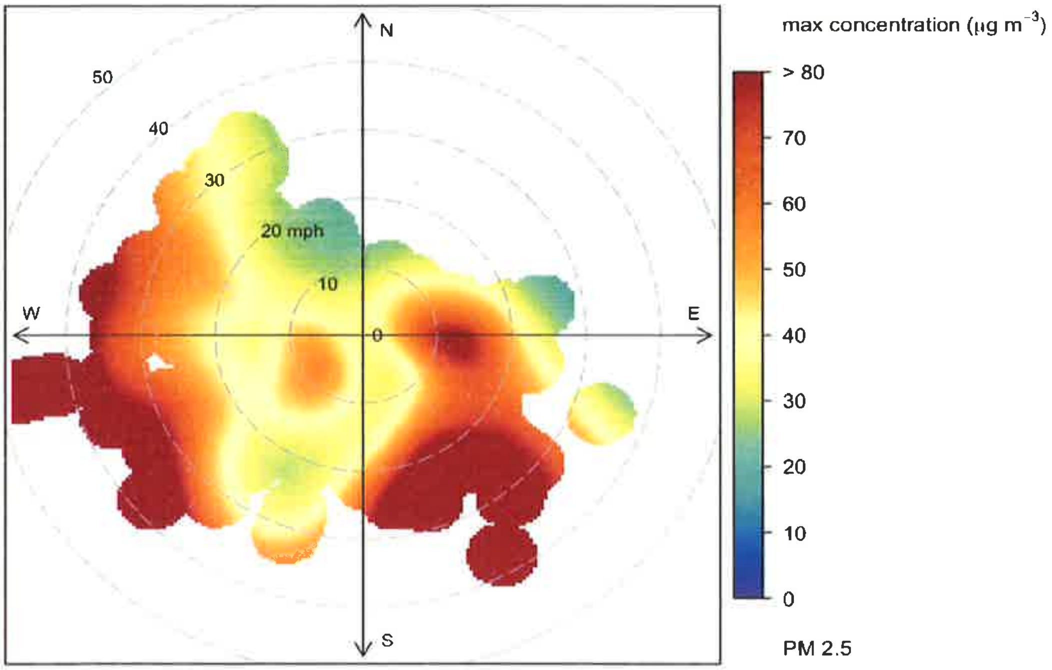


Figure 11: Counselor West (CW5) – highest recorded $PM_{2.5}$ levels P567

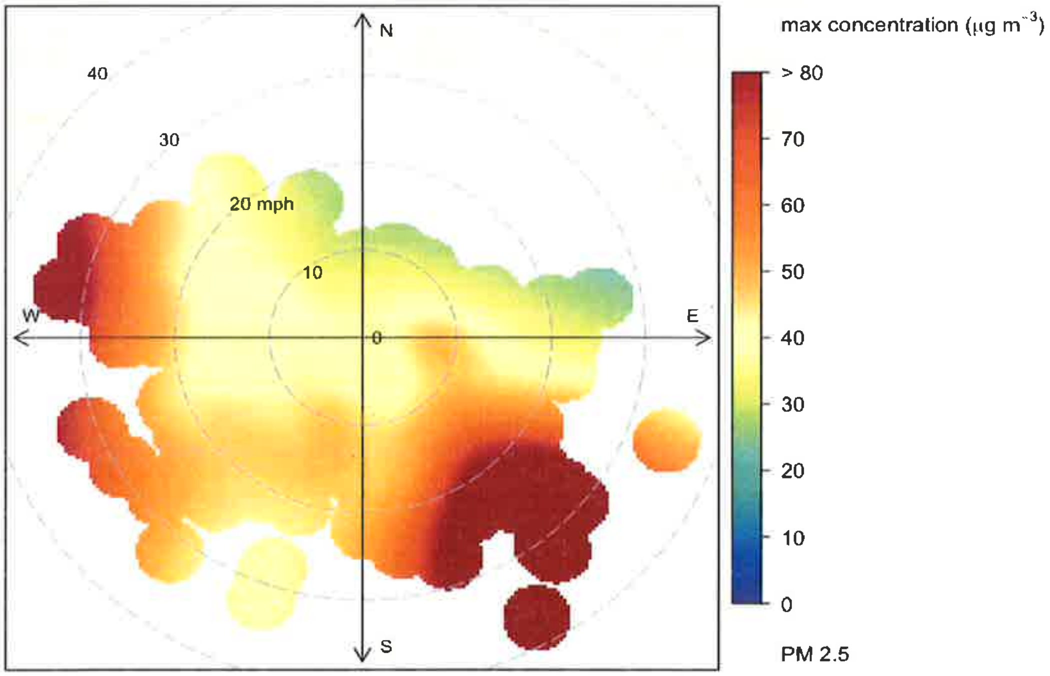


Figure 12: Counselor Highway (CCH6) P560

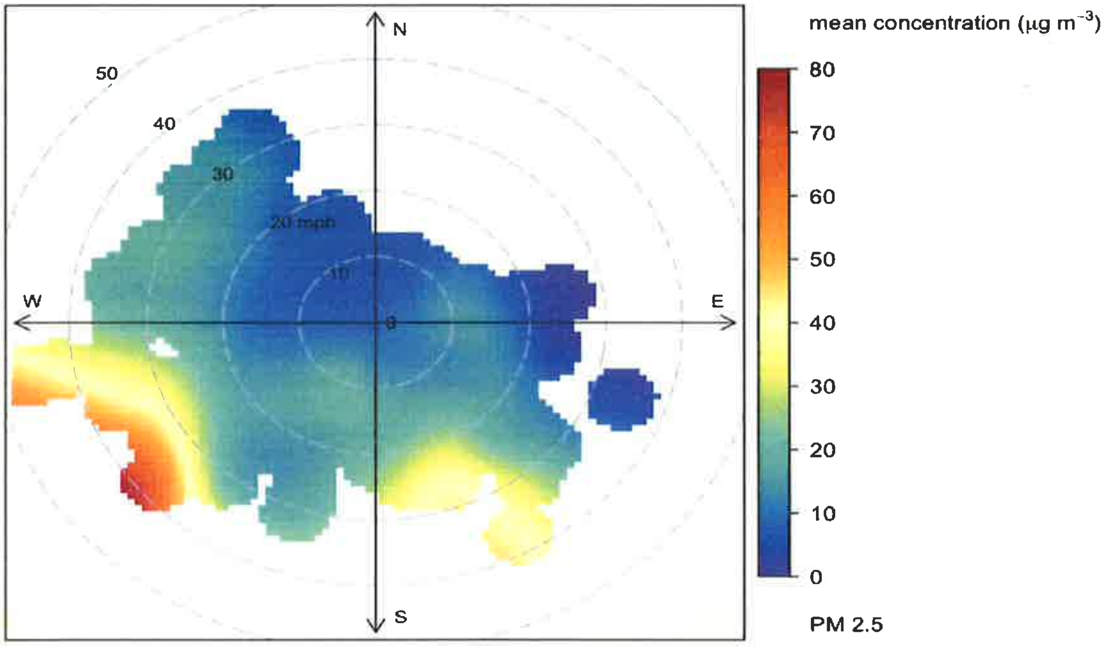


Figure13: Counselor Highway (CH7) – lowest recorded $PM_{2.5}$ levels P572

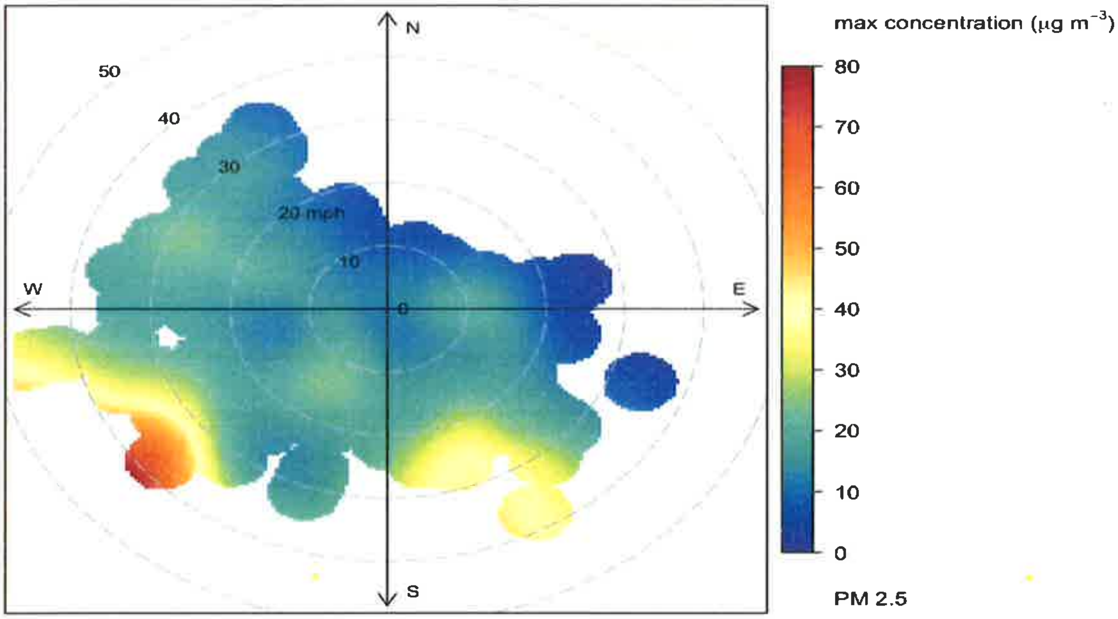
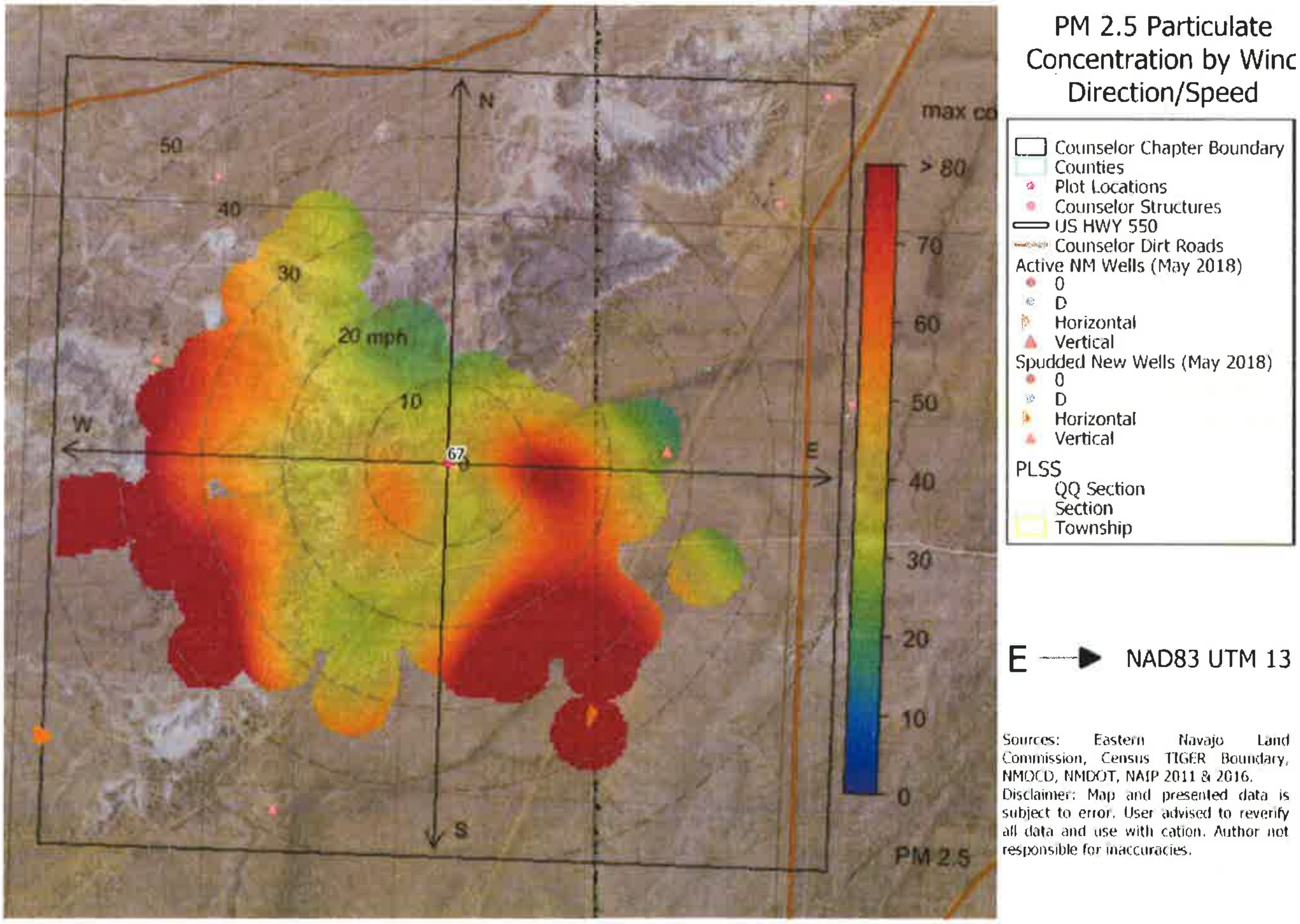


Figure 14: Counselor Highway (CH9) P570

Figures 7 to 14 are Counselor monitoring sites. EHP's Particulate Matter Impact App pairs the Speck PM monitor results with local weather data to show which weather conditions bring higher levels of PM2.5 to each residence. If you take a closer look at Speck P567 you can see how wind direction and wind speed influence the PM 2.5 concentrations.

Each location shows s different level of exposure when paired with the weather app. Hazardous levels were reached on a few days in late April and early May when the weather was calm, cold, cloudy and snowy, keeping particulate matter and chemical emissions closer to the ground for longer periods of time.



Sources: Eastern Navajo Land Commission, Census TIGER Boundary, NMOCD, NMDOT, NAIP 2011 & 2016. Disclaimer: Map and presented data is subject to error. User advised to reverify all data and use with cation. Author not responsible for inaccuracies.

Figure 15: Close up Map of Location Speck PS67 with highest levels of PM 2.5

#67 Close up Map shows the wind speed, direction and intensity of PM 2.5 – ranging from lowest (blue) to yellow-green (which indicates the EPA level of PM 2.5 at 35 ug/m3, which can impact the respiratory health of individuals), to red (the highest level of exposure and hazardous to human health).

In this particular situation, PM 2.5 concentrations exceeding a hazardous level of 80 ug/m3 occurred from south-southwest at 30-50 mph, southeast at 20-40 mph, and east at 10-20 mph. The image above displays three important aspects of the outdoor Speck monitoring results: the direction from which the highest levels of PM2.5 come from; the intensity of the PM2.5 measurements; and the wind conditions at the times of exposure. In the image, the Speck monitor is located in the center where the lines cross. The endpoints of the lines represent the cardinal directions of North, South, East, and West with North at the top. The *intensity of PM2.5* levels is shown in the range of colors from blue (low exposure) to red (high exposure). The concentric circles represent the wind speed, with low wind speed near the center and higher wind speeds further out.

Significance of Exposure

1) The episodic **intense peak exposures produced from oil/gas well emissions may only last for a few minutes to an hour in Counselor. But, such exposures can cause acute health symptoms**, even though the total exposure averaged over a 24-hour period appears acceptable and falls within a limit below a current threshold to consider action to prevent immediate health impacts.

2) Weather plays a significant role in both the number and duration of peak exposures. The period chosen to conduct air sampling fell during the spring when high winds and low precipitation is normal in Counselor. Such conditions are not conducive to sampling for air pollutants that remain in the local area and are closer to the ground (and the monitors) on calm days with either cloud cover or rain and snow events. **Testing throughout the year would yield different and more accurate results.**

3) **Evidence of exposure to hazardous levels of VOC concentrations is very short lived in the bloodstream and blood samples must be taken within hours of a symptom or time of suspected exposure.** Most communities have no facility that can provide this highly specialized blood test and residents who cannot take time to take a sample are unable to provide this crucial evidence if they try to file a formal complaint. The complaints recorded in the health section of this report have all been made in person to an HIA Committee member conducting the health survey or to a Counselor Chapter representative.

V. Counselor Chapter Health Impact Assessment (HIA)

Background

Counselor Chapter initiated the Health Impact Assessment in 2016 with a series of brief Health Impact Reports, written to document the oil well impacts being reported to chapter staff. Residents who attended chapter meetings and commented at public hearings held by Bureau of Land Management and the Navajo Nation, contributed their concerns about fracking, air pollution, traffic, accidents and illness to these reports. After several presentations to the Oil Conservation Division (EMNRD) and the Air Quality Bureau (NMED), in 2016-2017, a loosely organized committee formed in Counselor to start a formal HIA and do a community air quality study with the assistance of the Southwest Pennsylvania Environmental Health Project.

Sampling Strategy

The study focused on Counselor as the most heavily developed chapter with the highest number of active wells in the Tri-Chapter area of Counselor, Ojo Encino and Torreon. Participants in the study were landowners who lived within one mile of an active well and who volunteered to have a pair of Speck monitors placed inside and outside their home for a 32-45 day period to gather data on indoor and outdoor quality. After air sampling was completed and preliminary results released to the chapter, community residents were asked if they wanted to participate in a written health survey.

Community Health Survey

The purpose of the research, the health survey and Informed Consent forms were explained and provided to all participants. Confidentiality and the Rights as a Volunteer Participant were reviewed. A 28-question survey, listing 20 medical symptoms most commonly reported by people living near oil well operations, was completed by residents at each of the eight (8) air quality monitoring sites as well as by 57 attendees of chapter meetings in July and August of 2018 and 14 additional chapter residents who submitted survey forms directly to chapter staff following community events such as the Wellness Walk in May of 2018.

A total of 80 respondents represent 11.4 % of the population (700) of Counselor.

80 respondents were asked to indicate if they lived "near" (within 5 miles or within sight, hearing or smell) any of the following drilling or gas and oil infrastructure with the following responses:
Well Pad: 67 yes, 13 no (84% live near a well pad)
Pipeline: 53 yes, 27 no (66% live near a pipeline)
Processing Plant (refinery): 1 yes, 79 no
None lived near a Wastewater pond: 0 yes, 80 no
None lived near a Compressor station: 0 yes, 80 no

Respondents then recorded all the health symptoms they experienced in the past year since drilling began near their home.

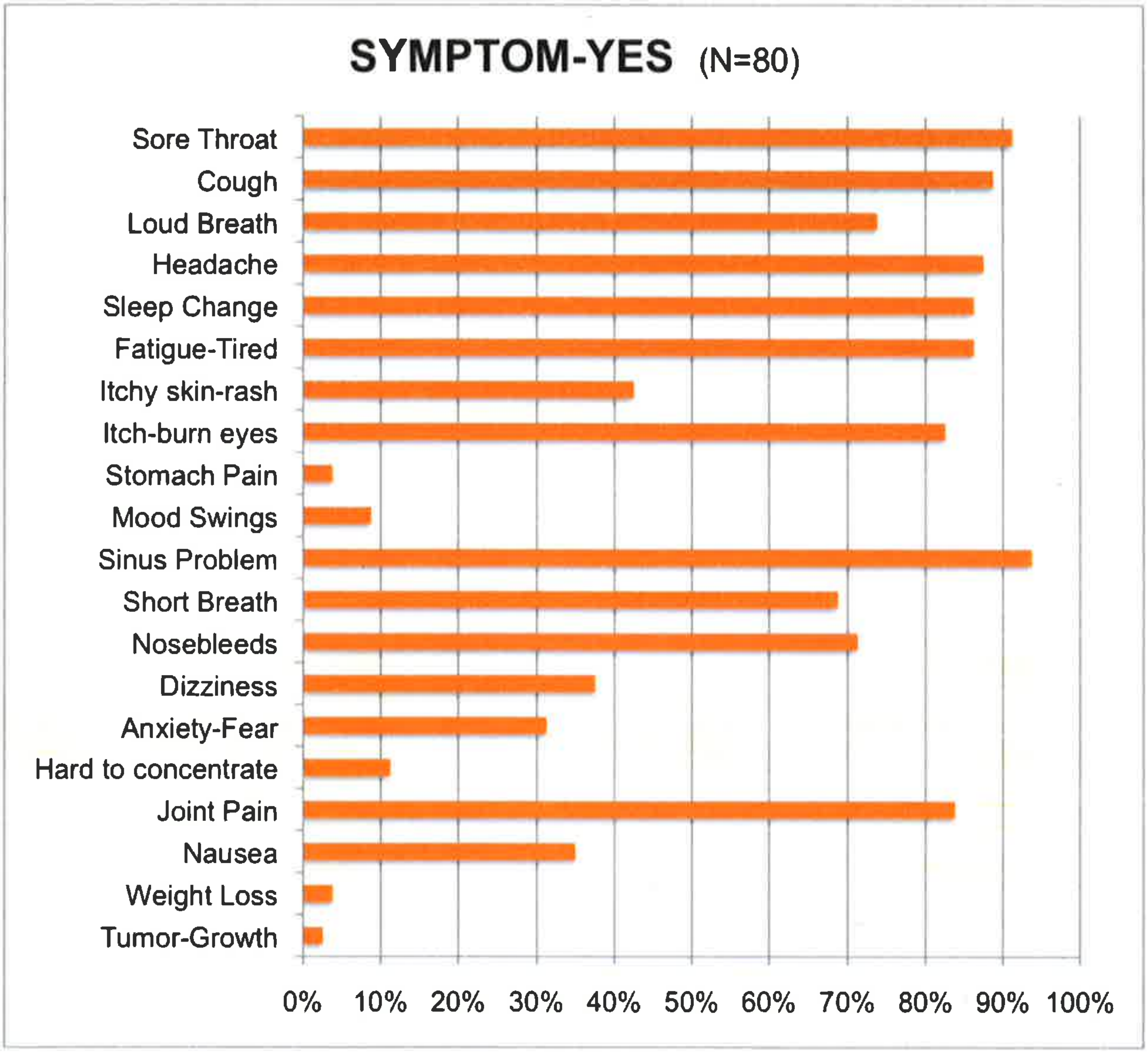


Figure 16: 20 recorded health issues with highest recorded symptom: Sinus Problem

Highest Recorded Symptoms:

- > 90% reported sinus problem (discharge, obstruction and pain)[5] and irritated/sore throat
- 80% reported cough, headaches, itching/burning of eyes, joint pain, fatigue & sleep disturbance
- > 70% reported nosebleeds and wheezing (loud breathing)
- > 60% reported shortness of breath
- 42% reported itching of skin/rash

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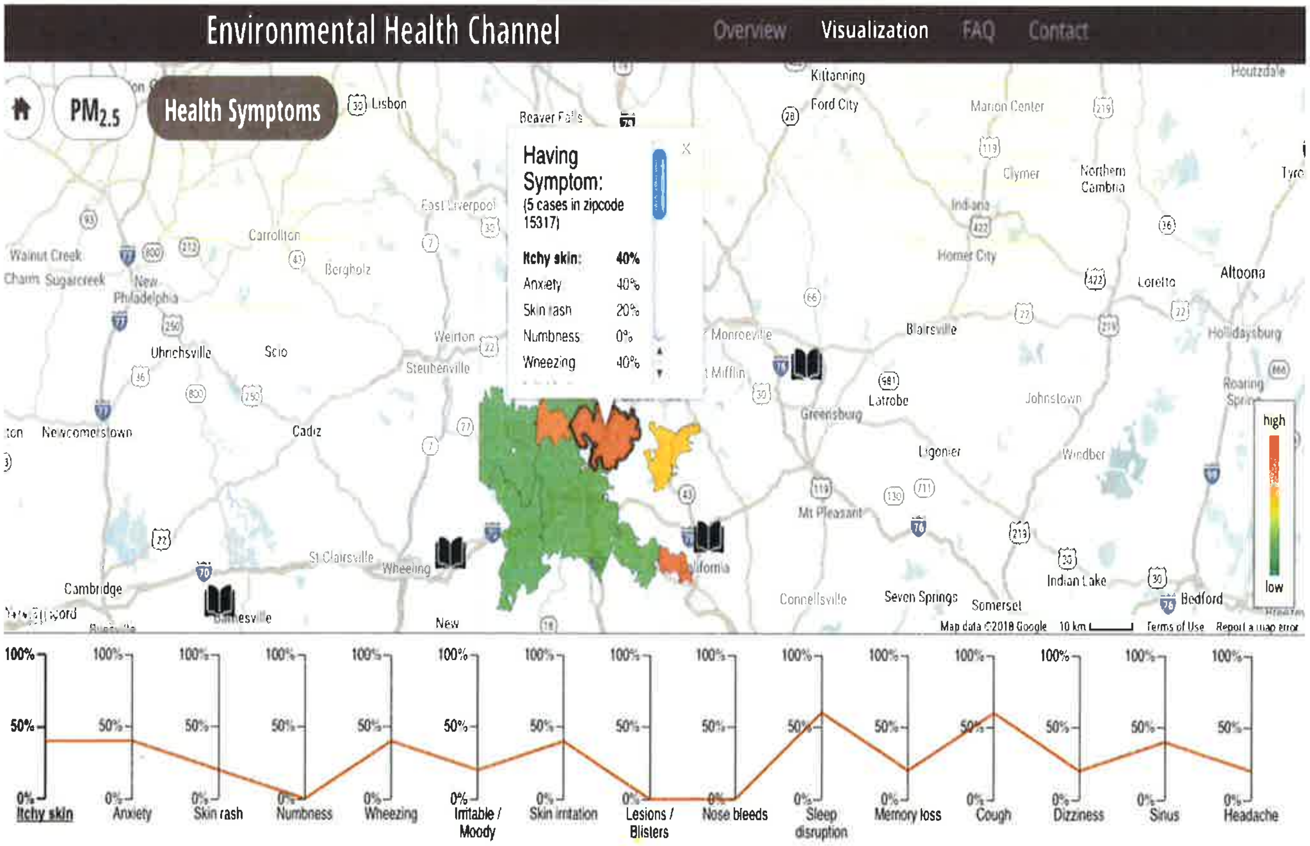
[5] "Associations between Unconventional Natural Gas Development and Nasal and Sinus, Migraine Headache, and Fatigue Symptoms in Pennsylvania". Aaron W. Tustin, et al, *Environ Health Perspect* DOI: 10.1289/EHP281.

- > 30% reported dizziness, nausea and feelings of anxiety/fear
- 11% reported difficulty in concentrating
- Other less reported (< 10%) symptoms: mood changes, stomach pain, weight loss or tumors/growths
- Four Counselor health survey respondents who did not live near wells reported either no health symptoms (2 respondents), 2 symptoms (1 respondent) or 3 symptoms (1 respondent), as contrasted with the average of 11 or more symptoms reported by residents who live near wells.

Survey Results and Comparison with National Database

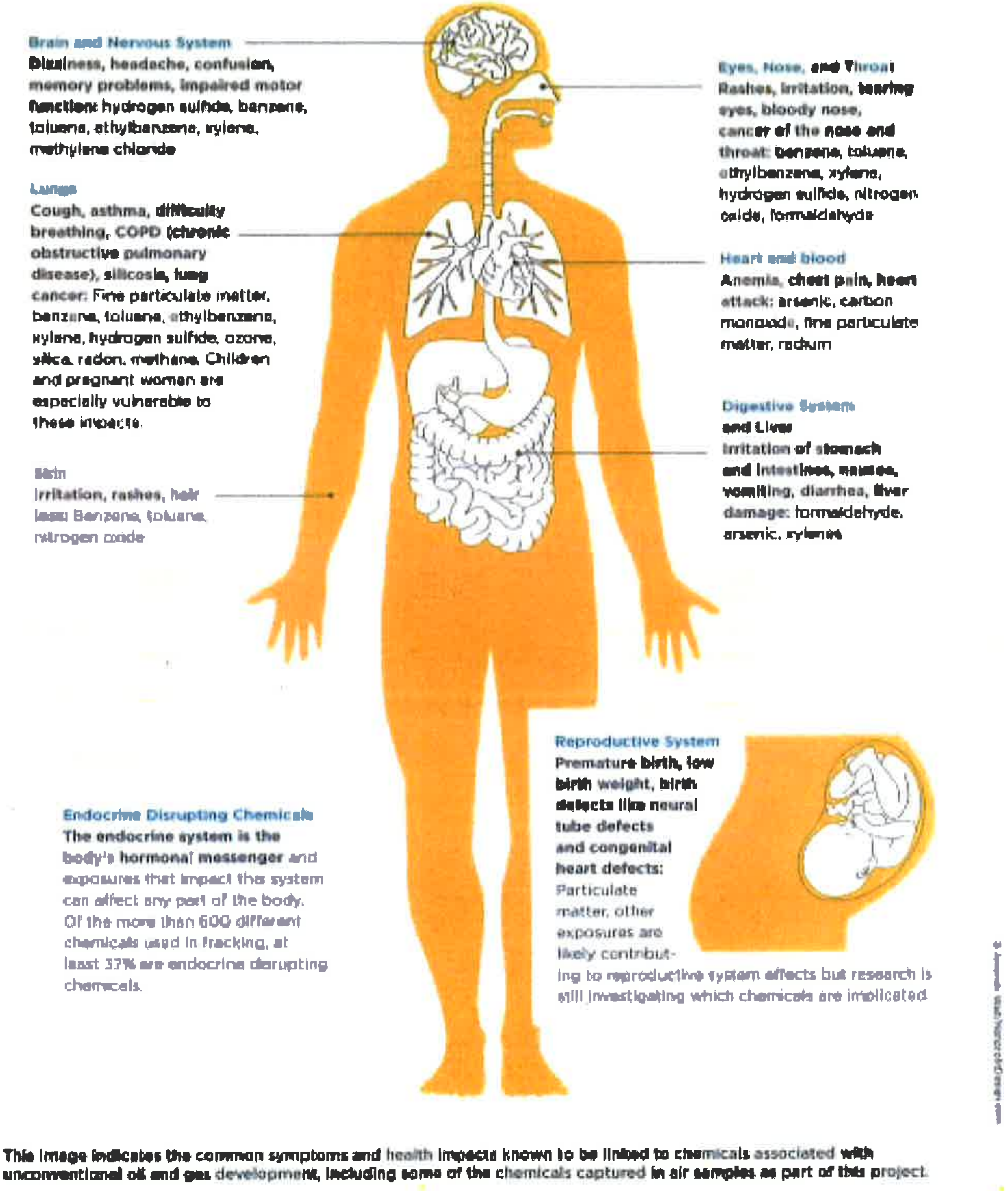
Over 60% of health survey respondents reported they experienced 11 out of a total of 20 listed symptoms. This a greater number of health symptoms reported by Counselor residents compared to other residents living next to gas and oil wells. The same 20 symptoms, surveyed by EHP nationally in similar communities, were reported by less than 50% of the respondents for any given symptom. Example: > 88% of Counselor respondents experienced sinus problems, sore throat and cough compared to the average of <60% of respondents in Washington County.



Having Symptom:
(5 cases in zipcode 15317)

Itchy skin:	**40%**
Anxiety	40%
Skin rash	20%
Numbness	0%
Wheezing	40%

Figure 17: Environmental Health Channel screen shot of Health Symptoms recorded from residents in Washington County, Pennsylvania.



Brain and Nervous System
Dizziness, headache, confusion, memory problems, impaired motor function: hydrogen sulfide, benzene, toluene, ethylbenzene, xylene, methylene chloride

Lungs
Cough, asthma, difficulty breathing, COPD (chronic obstructive pulmonary disease), silicosis, lung cancer: Fine particulate matter, benzene, toluene, ethylbenzene, xylene, hydrogen sulfide, ozone, silica, radon, methane. Children and pregnant women are especially vulnerable to these impacts.

Skin
Irritation, rashes, hair loss: Benzene, toluene, nitrogen oxide

Eyes, Nose, and Throat
Rashes, irritation, tearing eyes, bloody nose, cancer of the nose and throat: benzene, toluene, ethylbenzene, xylene, hydrogen sulfide, nitrogen oxide, formaldehyde

Heart and blood
Anemia, chest pain, heart attack: arsenic, carbon monoxide, fine particulate matter, radium

Digestive System and Liver
Irritation of stomach and intestines, nausea, vomiting, diarrhea, liver damage: formaldehyde, arsenic, xylenes

Endocrine Disrupting Chemicals
The endocrine system is the body's hormonal messenger and exposures that impact the system can affect any part of the body. Of the more than 600 different chemicals used in fracking, at least 37% are endocrine disrupting chemicals.

Reproductive System
Premature birth, low birth weight, birth defects like neural tube defects and congenital heart defects: Particulate matter, other exposures are likely contributing to reproductive system effects but research is still investigating which chemicals are implicated

This image indicates the common symptoms and health impacts known to be linked to chemicals associated with unconventional oil and gas development, including some of the chemicals captured in air samples as part of this project.

Figure 18: Counselor Health Survey included a body graphic so respondents could draw circles around parts of the body where they experienced symptoms. 100% of 57 respondents who chose to complete this page circled the head, 92% circled the lungs and 40% circled the skin.
(Graphic courtesy of Coming Clean, Inc.)

VI. SUMMARY OF RESULTS

Potential Childhood and Birth Outcomes Due to Exposure to Well Emissions

The majority of locations sampled in Counselor had higher particle concentration (ug/m^3) in their Baseline Air Quality and higher Accumulated Particle Matter (mg/m^3/day) than in similar locations monitored in other states. Newborns and young children are especially sensitive to well emissions and highly at risk. Exposing them to burning hydrocarbons from gas and oil well emissions puts them at greater risk than adults for both short- and long-term health effects.

Six large, well-conducted studies have been published on the effects of shale gas and oil development activity and birth outcomes. The studies found a range of overlapping outcomes associated with proximity to well pads, including low birth weight, low APGAR scores, prematurity, and neural tube defects. [6]

Children do not respond to emissions as though they are little adults. Instead:

- Children have higher respiratory rates and as a result children exposed to air contaminants breathe in more toxics per pound of body weight than adults.
- Children accumulate more toxics in their bodies than adults. Their bodies are still maturing and they cannot metabolize some toxicants as well as adults. They don't detoxify as efficiently.
- Children spend more time engaged in vigorous activity outside, increasing their exposures.
- Children's brains are still developing. Many toxic agents are known to interfere with developmental processes within the brain.

Children under the age of 9 years make up approximately 31% of the population of Counselor. Their well-being and future health and development is the highest rated concern of Counselor residents.

Health Effects from Exposure to Volatile Organic Compounds (VOCs)

VOCs, present at gas and oil wells, are a varied group of compounds that can range from having no known health effects to being highly toxic. **Short-term exposure can cause eye and respiratory tract irritation, headaches, dizziness, visual disorders, fatigue, loss of coordination, allergic skin reaction, nausea, and memory impairment or inability to concentrate.** Long-term effects include loss of coordination and damage to the liver, kidney, and central nervous system.

The above symptoms caused by episodic exposure to VOCs were recorded by > 80% of Counselor residents that participated in the health surveys conducted from May through August 2018 by the Counselor HIA Committee.

Further air quality testing and voluntary on site blood sampling from residents, for VOC levels, is needed to determine the actual degree of individual exposure and potential harm.

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[6] Hu, Howard, James Shine, and Robert O. Wright. "The Challenge Posed to Children's Health by Mixtures of Toxic Waste: The Tar Creek Superfund Site as a Case Study." *Pediatric Clinics of North America* 54, no.1 (February 2007): 155-175, x. doi: 10.1016/j.pcl.2006.11.009.

VII. Community Recommendations

Mitigation Measures Recommended for Community Health and Safety

The Counselor HIA Committee has worked closely for several years with the residents of Counselor and in 2018 with the Environmental Health Project (EHP), a public health organization working at the forefront of the nation-wide response to health impacts from unconventional oil and gas development (UOGD)

Based on 1) written comments, resolutions and memorials from Navajo Chapters and other elected leaders and representatives from the Navajo Nation and New Mexico Legislature; 2) results from the air monitoring project conducted by the Counselor HIA Committee; 3) health surveys completed by the Counselor Chapter; 4) and national research conducted by organizations and academics that have published in peer-reviewed literature, this report recommends the following mitigation measures to protect public health:

1. The most effective method to prevent toxic exposures for nearby residents is to trap emissions at the source. Emissions should be contained on all polluting equipment including wellheads, tanks, compressors, and pipeline valves.

2. Continuously monitor air emissions at UOGD sites for volatile organic compounds (VOCs), formaldehyde and fine particulate matter ($PM_{2.5}$). Monitoring should provide minute-by-minute data and the data should be analyzed to show the frequency, intensity and duration of peak emissions in addition to long term averaged exposures. These peak periods can cause dangerously high exposures for residents, especially children and individuals with pre-existing conditions, and are important health data for medical diagnosis.

3. Continuously monitor for VOCs, formaldehyde and PM at nearby schools, daycares, nursing homes where health-sensitive individuals are located. Develop emergency plans for these locations in the event of high exposure scenarios.

4. Provide indoor air filters for residents within 1/2 mile of UOGD sites. Include the provision of replaceable filters and maintenance for the indoor air equipment.

5. Establish a setback distance minimum of 1/2 mile (2640 feet) from smaller shale gas facilities, such as wells, that emit 100 to 500 grams/hour.

6. Establish a setback distance minimum of 1 1/4 mile (6600 feet) for gas processing plants and large compressor complexes whose emissions exceed 1000 grams/hour.

7. Require windbreaks around UOGD sites that are located on plateaus, plains or other geographic areas that do not provide physical barriers between sites and residential areas.

In addition:

- Complete the recommended steps on the HIA Assessment Checklist to adequately inform community residents of all the known and unknown risks they are being asked to assume.
- Perform an in-depth air emission projection to establish the local population health risk to cumulative effects before additional wells are drilled.
- Require best practices to ensure that effective emissions control measures are kept up to date.
- ALERT residents via the Chapter ALERT website of large emission events.
- Put emergency plans in place in case of evacuation.
- Institute a monitoring strategy at well sites and key public locations and make the data public on the Chapter website.
- Institute a health-monitoring registry at the local Indian Health Clinic to include short- and long-term effects.
- Facilitate voluntary blood sampling by providing "on-site" facility (within a one-hour drive) that can test exposed individuals for VOC levels and monitor symptoms and treatments.

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APPENDICES

Appendix 1
ALS Environmental: Report #1806078, NCP-Navajo Community Project (QC sample results and case narrative) June 18,2018. Pgs. 1-25; ALS Environmental: Report 18051137. June 13, 2018. Pgs.1-12.
Appendix 2
Southwest Pennsylvania Environmental Health Project Report: "Counselor Chapter Air Quality Assessment Results: Particulate Matter (PM2.5) and Volatile Organic Compounds (VOCs)", (August 3, 2018) pgs. 1-14
Appendix 3
Navajo Nation Environmental Protection Agency Air Quality Control Program "Ambient Air Monitoring, Counselor, NM" (April 14, 2016-May 18, 2017) pg. 1-2
Appendix 4
New Health Issues for Counselor – Produced Water & Water Monitoring

ACRONYMS

US EPA	United State Department of Environmental Protection
ATSDR	Agency for Toxic Substances and Disease Registry of the Centers for Disease Control and Prevention
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PEL	Permissible exposure limits
REL	Recommended exposure limit
$\mu g/m^3$	Micrograms per cubic meter→ air quality measurement
ppm	parts per million
ppb	parts per billion