

OCC Hearing Exhibit 21

From: [Davidson, Florene, EMNRD](#)
To: [Salvidrez, Marlene, EMNRD](#)
Subject: FW: [EXT] Science Journalist & Author Seeking to Make Comment At Thursday's Public Hearing on Oil & Gas Produced Water, Documents Attached
Date: Tuesday, July 28, 2020 1:53:08 PM
Attachments: [Peter Gray NORM Contamination in the Petroleum Industry, 1993 Society of Petroleum Engineers.pdf](#)
[1982 API Analysis of RADIONUCLIDES in oil and gas industry.pdf](#)

Case 21281

From: Justin Nobel <justinnobel@gmail.com>
Sent: Tuesday, July 28, 2020 12:22 PM
To: Davidson, Florene, EMNRD <florene.davidson@state.nm.us>
Subject: [EXT] Science Journalist & Author Seeking to Make Comment At Thursday's Public Hearing on Oil & Gas Produced Water, Documents Attached

Dear Florene,

I hope this note finds you well. I write on issues of science and the environment for a number of different US magazines and investigative sites and for the past three years I have been researching and reporting on the topic of the radioactivity brought to the surface in oil and gas production and the many different pathways of contamination posed to the industry's workers, the public and communities and the environment. It's a complex and far-reaching topic. In January I published a lengthy article with Rolling Stone magazine, [America's Radioactive Secret](#), and I am presently working on a book to be published with Simon & Schuster. In my reporting and research I have gained a significant expertise in the topic of oilfield waste, including waste streams such as produced water, and I am looking to join the list of commenters for the **Thursday July 30th Public Hearing on the Proposed Rule Regarding Oil & Gas Industry Produced Water**.

Attached are two important early oil and gas industry documents that I plan to refer to in my comments. If you could please make sure these documents are made available to the public and members of the Commission. I will submit my written comments upon making my statement, as appropriately directed by you. Please let me know if you have any additional questions.

Thanks very much for your time and attention.

Sincerely,
Justin Nobel

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NORM Contamination in the Petroleum Industry

P.R. Gray, SPE, Peter Gray & Assocs.

Summary. Contamination of oil and gas facilities with naturally occurring radioactive materials (NORM) is widespread. Some contamination may be sufficiently severe that maintenance and other personnel may be exposed to hazardous concentrations. Contamination with radium is common in oil-production facilities, whereas contamination with radon and radon decay products is more prevalent in natural-gas production and processing facilities. Although largely unregulated until recently, U.S. states, notably Louisiana and Texas, have or are enacting legislation to control NORM contamination in the petroleum industry.

Introduction

NORM contamination can be expected at nearly every petroleum facility. Some of it can be sufficiently severe that maintenance and other personnel may be exposed to hazardous concentrations. In addition, the industry must comply with new regulations. Mississippi and Louisiana have enacted legislation to control NORM; Texas will have regulations early in 1993; and other states, as well as Canada, can be expected to have similar regulations shortly.

Two general types of common NORM contamination will be controlled by these regulations.

1. Radium contamination of petroleum production facilities—specifically of pipe scale and sludge and scale in surface vessels. In addition, produced water may be radioactive from radium dissolved in underground water.

2. Radon contamination of natural-gas production facilities. This includes contamination with the long-lived decay products of radon. Facilities that remove ethane and propane from natural-gas facilities are especially susceptible to NORM contamination.

Naturally occurring radionuclides are widespread in the environment. In many geologic formations, radium, radon, and other radioactive elements are associated with oil and gas. When oil and gas are produced, traces of these radioactive elements also are produced. When the formation water contains traces of radium (radium-226, a decay product of uranium, and radium-228 from thorium), scale in the production pipe can become radioactive, sometimes containing several thousand picocuries of radium per gram of scale.^{1,2} The radioactivity results when radium coprecipitates with barium and strontium sulfates in the scale formation.

Radium also can contaminate scale and sludges in surface equipment by similar mechanisms, including carbonate precipitates and sulfate deposits. Produced water may contain dissolved radium. This can lead to contaminated sludges in waste pits and radioactive water.

Contamination of gas wells, pipelines, and gas processing facilities results primarily from radon produced with natural gas.³⁻⁶

NORM Contamination

NORM contamination in the oil and gas industry commonly occurs as radioactive scale, films, and sludges.

Radium-Contaminated Scale and Sludge.

Radioactive scale can contain uranium, thorium, radium, and associated decay products from the production of oil and associated brines contaminated with NORM. The radioactivity in the scale in production pipe originates mainly from radium, which coprecipitates with barium and strontium sulfate. Other isotopes in the uranium-238 and thorium-232 decay series also may be present. Contaminated scale may contain up to several hundred thousand picocuries of radium per gram of scale.

Radioactive scale may be found in surface processing and transport equipment and in downhole tubing. For example, piping, sludge pits, filters, brine disposal/injection wells, and associated equipment may be contaminated with radium NORM. Also, soils and equipment contaminated from well tubing workovers conducted to remove scale—both at the wellsite and at remote pipe cleaning yards—may be contaminated with NORM.

Films. Radioactive films, coatings, or plating can form from natural-gas production or processing. Often invisible to the naked eye, these films contain radon and its decay products, normally with no radon precursors (e.g., radium) associated with them. Because of radon contamination in natural gas, these radioactive films can be found at gas wellheads; in transport piping, headers, treater units, and pumps; and within natural-gas processing plants or other light-hydrocarbon facilities.

Sludge Contaminated With Decay Products of Radon.

Radioactive sludges in pipelines, processing plants, natural-gas liquid (NGL) storage tanks and delivery facilities, pigging operations, and gas lines and other filter assemblies can be contaminated with

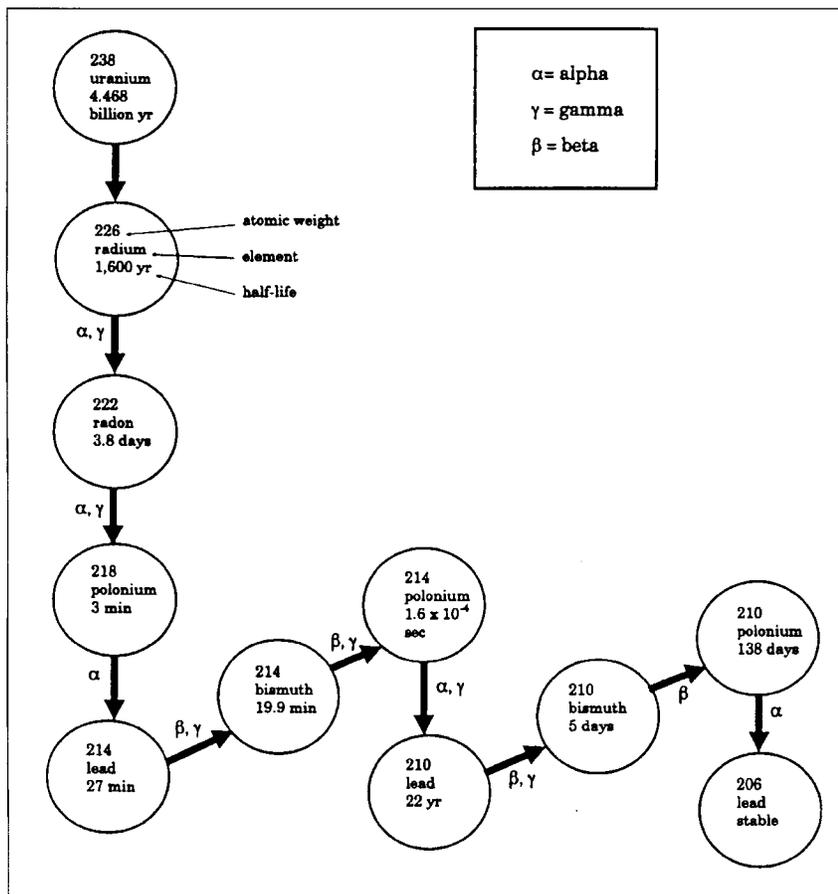


Fig. 1—Radioactive decay of uranium-238.

radon in the natural gas. Sludges also may be contaminated with several thousand picocuries per gram of the long-lived radon decay products (i.e., lead-210, bismuth-210, and polonium-210). These heavy-metal decay products may attach to dust particles and aerosols to become part of the sludge.

Filter assemblies in gas lines remove the radon decay products from the gas with other particulate matter and can become very radioactive.

History of NORM Contamination

Radium has been known as a trace contaminant of underground water for a long time but wasn't reported to be a contaminant of scale until the early 1980's, when the problem was first reported in the North Sea. Radon contamination of natural gas has been known for nearly 100 years.⁷ However, it was only in 1971 that radon was found to concentrate in the lighter natural-gas liquids during processing and could present a serious health hazard to industry personnel, particularly maintenance employees.

Some radon was undoubtedly removed with the NGL's before 1971. However, deep extraction techniques developed to remove more ethane from the gas also extracted significantly greater concentrations of radon. The problem was discovered when the radon contamination in propylene became sufficiently high to interfere with liquid level sensors detecting slurry levels in a polypropylene plant.

The radioactive scale problem in the oil and gas industry has been reported in the literature.^{1,2} With the notable exception of a 1975 report by Gesell⁸ and a paper by Gray⁹ in 1990, NORM contamination of gas facilities by radon and its decay products has not been as extensively reported.

Radium and Radon

Radium-226 is the fifth decay product of uranium-238, and radium-228 is the fourth decay product of thorium-232. Uranium and thorium are present in most soils and rocks in widely varied concentrations in the Earth's crust throughout the world. Some radium salts (e.g., radium chloride) are soluble in water, and underground water can dissolve the radium in the uranium and thorium formations. The radium may stay dissolved in the water as long as contact with sulfate and carbonate formations is limited. The radium-contaminated water may be produced with oil and gas.

Radon is a naturally occurring, highly mobile, chemically inert radioactive gas in the uranium-238 decay series. Radon-222 is produced by the radioactive decay of radium-226. Because radium is widely distributed in the Earth's crust, radon also is widely distributed. Recent reports of radon-contaminated buildings throughout the world attest to the wide distribution of radon in the environment. Radon is a noble gas, similar to helium and argon, and it is extremely un-

TABLE 1—RADON CONCENTRATIONS IN NATURAL GAS AT THE WELLHEAD*

Location of Well	Radon Concentration (pCi/L)
Borneo	1 to 3
Canada	
Alberta	10 to 205
British Columbia	390 to 540
Ontario	4 to 800
Germany	1 to 10
The Netherlands	1 to 45
Nigeria	1 to 3
North Sea	2 to 4
U.S.	
Colorado, New Mexico	1 to 160
Texas, Kansas, Oklahoma	1 to 1,450
Texas Panhandle	10 to 520
Colorado	11 to 45
California	1 to 100

*From *Radon Concentrations in Natural Gas at the Well*, U.N. Scientific Committee on the Effects of Atomic Radiation; Sources and Effects of Ionizing Radiation, United Nations, New York City (1977).

TABLE 2—BOILING POINTS AT 760-mm MERCURY

	°F
Methane	-258.0
Ethane	-124.0
Radon	-79.2
Propylene	-53.9
Propane	-44.4
Butane	+31.1

reactive chemically. Once formed by the radioactive decay of radium-226, radon is free to migrate as a gas or dissolve in water without being trapped or removed by chemical reaction. Migrating through rocks and soil, radon is produced with natural gas at the wellhead. Table 1 shows that radon contamination of natural gas is a worldwide problem, and particularly high concentrations of radon are reported in the U.S. and Canada.

When radon-contaminated produced gas is processed to remove the NGL's, much of the radon is removed also. Radon's boiling (or condensing) point is intermediate between the boiling points of ethane and propane. Upon subsequent processing, radon tends to accumulate further in the propylene distillation stream. Table 2 shows the boiling points of radon, the lighter NGL's, and propylene. As expected, radon usually is recovered more completely in plants with high ethane recovery. The radon is concentrated in the lighter NGL's and is detected relatively easily with radiation survey meters.

As long as it is contained and controlled within vessels, equipment, and piping, radon generally is not a health hazard to employees and the public. Even if radon-contaminated propane were released, the threat of fire or asphyxiation would far outweigh the hazard of a short-lived radiation exposure.

Although other radon isotopes exist [e.g., radon-220 (thoron)] from the decay of thorium-232, the only radon isotope of concern

TABLE 3—PRIORITY AREAS OF CONCERN FOR HIGH RADON AND RADON DECAY PRODUCT CONTAMINATION

NGL facilities
De-ethanizers
Stills
Fractionators
Product condensers
Flash tanks
Pumps in liquid service
Piping in liquid service
NGL storage tanks
Truck terminals
Filter separators
Dessicants
Waste pits
Pipelines
Filters
Pig receivers
Machine shops
In-house
Contract

is the 3.8-day half-life radon-222. Radon-220 and other radon isotopes have very short half-lives and will have decayed before the gas is produced at the wellhead. Because the half-life of radon-222 is 3.8 days, 99% of the radon will decay to its long-lived lead-210 decay product in 25 days.

Radon Decay Products

Radon itself is not a particularly hazardous material. Because it is chemically unreactive, it does not accumulate in the body. The health hazards associated with radon exposure are from its decay products. These long-lived radioactive materials present a growing problem to the industry, especially to personnel who may be exposed to contaminated surfaces, sludges, and other waste materials. Fig. 1 shows each atom of radon-222 eventually decays to an atom of lead-210 and subsequently to bismuth-210 and polonium-210 before decaying to stable lead-206. The half-life of lead-210 (a solid metal material) is 22 years. Therefore, the concentrations of radioactive lead, bismuth, and polonium will continue to increase in pipelines, gasoline plants, tank cars, and trucks for more than 100 years.

Contaminated facilities and waste-material problems must be recognized and addressed. The presence of the radioactive metals from radon decay cannot be detected on the outside of contaminated equipment and vessels. Unlike radon, the radiations that the decay products emit are easily absorbed by the walls of the equipment. If present in sufficiently high concentrations, radon can be detected externally to storage vessels, pumps, etc. Radon has moderately energetic gamma radiation in its decay that can be detected with gamma survey meters.

If an alpha/beta probe is held close to contaminated internal surfaces and concentrations are sufficiently high, survey meters may detect the presence of the radon decay products. However, laboratory analyses are

usually required to determine concentrations of lead, bismuth, and polonium accurately.

These radioactive materials are not a health hazard unless they are ingested or inhaled into the body—e.g., during repair and maintenance on the facility. If inhaled, the dust and aerosols containing NORM can attach to the lung surfaces, where they emit alpha radiation into the tissue of the lung lining. Studies of uranium miners indicate that extended exposure to these radon decay products pose an increased risk of lung cancer.^{10,11}

NORM in NGL Facilities

Although entire natural-gas and NGL systems may be contaminated with NORM, some facilities will be contaminated to the extent that they present significant decontamination and disposal problems. Gasoline plants and other NGL facilities will be among the most highly contaminated areas in a system.

During processing in a gasoline plant, the levels of external radiation from radon in propane 1 ft from a liquids pump may be as high as 25 milliroentgens (mR)/hr. Radiation levels up to 6 mR/hr have been detected at outer surfaces of storage tanks containing fresh propane. Sludges in gasoline plants are often contaminated with several thousand picocuries of lead-210 per gram.

Table 3 shows vessels and equipment in NGL service that may be significantly contaminated with NORM. Although NORM contamination will be general throughout an NGL facility, the contamination usually will be greatest in areas of high turbulence, such as in pumps and valves.

When employees open equipment and vessels, precautions must be taken to prevent exposure to radioactive contamination.¹² Maintenance procedures should include the use of respirators and good hygiene to prevent inhalation of radioactive dust. Grinding, if necessary, should be done wet to minimize dust.

Occasionally, a plant or other facility that has been processing light hydrocarbons, particularly ethane and propane, is taken out of service and the facility sold or dismantled. Any equipment with internal surface deposits of NORM must receive special consideration when scrapped, sold, transferred, or otherwise disposed of, particularly when the facility is being released for unrestricted use. Analyses for lead-210 usually will be required to verify the extent of contamination and to determine if special handling is needed. Particular care must be used to prevent employee exposure to NORM contamination.

There are potential liabilities involved if contaminated equipment, vessels, and other parts of the facility are released or sold for unrestricted use without first being cleaned and tested to be essentially free of NORM contamination according to state and federal regulations.

Much of the material wastes from a facility contaminated with NORM must be

handled as low-level radioactive waste and disposed of accordingly. Contaminated wastes should be consolidated and separated from noncontaminated waste to keep radioactive waste volumes as low as possible. Consolidated contaminated wastes should be stored in a controlled-access area. The area should be surveyed with a radiation survey meter and, if required, should be posted according to state and federal regulations.

Other NORM Contamination

Besides vessels and equipment in NGL service, other facilities susceptible to significant contamination include pigging operations, machine shops, and filter assemblies.

Pipeline sludges can obtain small radium-226 concentrations together with a few hundred to several thousand picocuries of radon decay products per gram. These sludges require the same handling as low-level radioactive wastes. The pig itself may be contaminated. This may require handling the pig with gloves and storing it in an area with restricted personnel access.

Machine shops present a special NORM situation. For example, pumps in NGL service may be among the most highly contaminated equipment in a plant. Occasionally, these pumps may need to be checked for leaking seals or impeller balance. NORM contamination inside a pump is often chemically bonded to the pump structural metal and cannot be easily removed without scraping and grinding. Because rebalancing is usually done by grinding until balance is established, the grinding may generate significant quantities of radioactive dust that can contaminate personnel as well as the shop facility. This can pose a very serious problem if contract machine shops are used.

Although pipelines and equipment in dry-gas service may be only marginally contaminated, filter assemblies in dry-gas service may be contaminated with very high concentrations of NORM and require special handling to prevent inhalation of the radioactive dust and contamination of the environment during changing of the filters and other required maintenance.

Radiation Surveys

NORM contamination is detected by radiation surveys with Geiger-Mueller or scintillation probes on a suitable survey meter. The gamma radiation emitted by radium and radon are sufficiently energetic that they are detected relatively easily if present in high concentrations. The radiations emitted by the decay products of radon are not easily detected. The radiations from lead-210 (low-energy gammas), bismuth-210 (betas), and polonium-210 (alphas) will not penetrate vessel and equipment walls and are detected only with low efficiency when a suitable probe (e.g., an alpha pancake probe) is used directly on the contaminated surface. Because these radon decay products are detected, at best, with low efficiency, any reading on the survey meter above background indicates significant contamination.

Samples should be taken and submitted to a laboratory for analysis. The exempt concentration levels for these radionuclides are very low, and contamination above the exempt concentrations is common. Because the radiations are easily absorbed, areal surveys of the ground and soil around petroleum facilities for radon-decay-product contamination are generally not meaningful and samples must be taken for laboratory analyses.

Radium and radon emit sufficiently energetic radiation to make their detection somewhat easier. The gamma rays will commonly penetrate structure walls, making external radiation surveys with Geiger-Mueller or scintillation detectors meaningful. The exempt concentrations in the Louisiana and Mississippi regulations and in pending regulations in other states are so low, however, that concentrations of radium and radon near the exempt levels are very difficult to measure accurately. A well-trained technician is required to make such surveys with confidence. Again laboratory analyses may be needed to determine accurately the amount of contamination. Such analyses are probably required when the facility or property is being sold, abandoned, or otherwise released. Accurate records of contamination will be required to prevent future litigation.

Disposal of NORM Wastes

The disposal of NORM-contaminated wastes is a major problem with no completely satisfactory solution. The disposal of NORM wastes is regulated by Louisiana and Mississippi and will be regulated in all other states as their regulations become effective. Options are limited. For example, the NORM wastes must be separated from non-NORM wastes and cannot be disposed of by "ordinary" methods of waste disposal, such as landfills. Disposal of contaminated wastes with uncontaminated material in a landfill or by other methods of disposal is not allowed unless the contamination level is below exempt concentrations in state and federal regulations. The few facilities licensed to accept NORM wastes are expensive to use and require a complete paper trail.

Although individual states or groups of states are obligated to have low-level radioactive waste repositories by 1993, these facilities may not accept NORM wastes from the petroleum industry. This is the case in Texas, for example, where the Texas Low Level Radioactive Waste Repository is designed to accept radioactive wastes from medical facilities, educational institutions, and industrial non-NORM wastes. The cost of disposal will be expensive—Texas estimates that the cost of storing radioactive wastes in its low-level repository will be about \$175/ft³.

Currently, the most economical and practical method may be to store the NORM wastes on the facility property in an area with controlled access. The revised Louisiana regulations address the disposal problem and require a proposed disposal plan be

submitted to the state within 90 days of the NORM generation.

It sometimes may be possible to dilute the wastes sufficiently with noncontaminated material so that the NORM concentrations are below exempt levels. For example, moderately contaminated soil may be diluted with noncontaminated soil or radium-contaminated water may be diluted with "clean" water. If sufficiently diluted, the resulting wastes may possibly be disposed of by ordinary methods.

Reinjection of radium-contaminated water is a possible solution to the disposal of such water. Injection of other NORM wastes (e.g., contaminated scale) in a Type II injection well may be the best possible disposal method for these wastes when allowed by the regulations.

The high cost of disposing of NORM wastes is opening new opportunities for R&D in methods and techniques for reducing waste volumes. For example, production waste may be contaminated above exempt levels with radium-226 and radium-228. If the radium could be removed from the water economically, the costs of disposing of the contaminated water would be reduced significantly. There are R&D ef-

"The high cost of disposing of NORM wastes is opening new opportunities for R&D in methods and techniques for reducing waste volumes."

orts in progress to do this, such as using resins and membranes to absorb or separate the radium from water and other corrosive liquids. Similar efforts are being applied to concentrate radium and lead-210 and its radioactive daughters from organic and inorganic sludges. If successful and economical, this may be a solution to the disposal of large volumes of NORM-contaminated wastes.

Decontamination of facilities by sandblasting can generate large volumes of NORM wastes. Novel methods of "sandblasting" with materials that will minimize the solid wastes are being explored. Reaming out scale from production pipe can generate large quantities of NORM wastes. Because only a fraction of the scale, possibly as low as 5% to 10%, may be contaminated above exempt concentrations, preliminary gamma surveys of the pipe to locate NORM sites can be used to guide reaming operations and to reduce NORM-contaminated scale wastes. Contaminated scale may be spotty (i.e., not uniform within the pipe), so the total joint should be surveyed on all sides. External scale on the pipe also can be contaminated with radium, necessitating careful handling to prevent ingestion or inhalation

of NORM dust and contamination of the environment.

As an alternative to reworking or cleaning of contaminated production pipe, the pipe can be left in place in the ground. It is not required to pull the pipe and remove the contaminated scale.

The trend in U.S. state regulations is toward more regulation and control of NORM wastes. NORM disposal will undoubtedly become very expensive.

Regulations

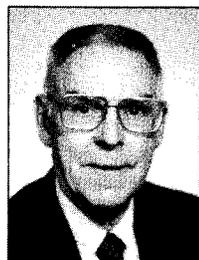
Radium and radon in oil and gas operations produce radioactive waste materials that contaminate facilities and equipment, exposing employees to hazardous materials and creating waste disposal problems. Such wastes and facilities should be treated as much as possible like other facilities and equipment covered by the U.S. Atomic Energy Act (e.g., soil contamination limits, criteria for facilities and equipment released for unrestricted use, and rules for proper handling and disposal of contaminated materials).

Several state and federal agencies have potential jurisdiction over NORM, but their application to NORM is unclear. NORM does not fall under the definition of source, special nuclear, or by-product material as currently defined in the Atomic Energy Act. Therefore, NORM is not subject to the Nuclear Regulatory Commission regulations. States have laws and regulations governing the use, possession, handling, and disposal of radioactive materials, but their application to NORM is still unclear. Except for Louisiana and Mississippi, no specific state regulations for the control of NORM contamination exist. Texas and several other states are expected to have NORM regulations in 1993. Louisiana specifically exempts the wholesale and retail distribution, possession, use, and transportation of oil and natural gas and NGL's from the regulations. The exemption, however, does not apply to contaminated facilities, such as pipelines, gasoline plants, and other physical facilities.

The Louisiana and Mississippi and other proposed state regulations are very specific regarding disposal of contaminated wastes and sale, abandonment, or release of facilities that may be contaminated. Companies doing production pipe cleaning and workovers must be specifically licensed, as do contractors supplying decontamination services. Louisiana has required radiation surveys of every petroleum facility in the state. As proposed, the Texas regulations will not require such extensive surveys. Texas will require surveys only of specific licensed facilities.

To ensure compliance, companies must be familiar with the regulations as they evolve. Although only Louisiana and Mississippi have regulations in effect, Texas, other states, and Canada are expected to have regulations soon for the control of NORM in the petroleum industry. The U.S. Environmental Protection Agency (EPA) is also

Author



Peter Gray is a consultant on NORM contamination in the petroleum industry. He retired in 1985 from Phillips Petroleum Co. where he was the principal investigator in Phillips' NORM control program. Gray holds BS and MS degrees from Michigan Technological U. and a PhD in nuclear chemistry from the U. of California at Berkeley.

considering enacting NORM regulations on the federal level.

Regulatory developments must be monitored as current knowledge of the NORM issues evolves. Where possible, industry input should be directed to minimize an over-regulation of NORM contamination in the industry.

Suggested Program for the Control of NORM

The following are suggestions for use in establishing a program for the control of NORM contamination.

1. Determine whether there is a NORM contamination problem.

2. Determine areas of potential NORM exposure and contamination.

A. Make gamma radiation surveys of facilities and equipment.

B. Make wipe tests on accessible interior surfaces of selected equipment and vessels, especially any in NGL service.

C. Obtain samples of sludges and scale and analyze for radium and lead-210.

D. Obtain samples of other waste materials, such as dessicants and filters.

E. Analyze produced water and waste pond water for radium.

3. Establish programs to ensure personnel safety, product quality, customer satisfaction, and protection of the environment.

A. Establish policy on periodic surveys, inspection and maintenance procedures, product controls, and record keeping.

B. Provide safety-manual material that informs employees and details required procedures, particularly for maintenance personnel.

C. Recommend a management and audit system.

D. Develop plans and procedures for the disposal of contaminated waste materials, equipment, and facilities.

E. Prepare a public relations release to use if questioned by employees, customers, the public, and the media.

4. Inform facility personnel of the possibility of NORM contamination.

5. Review governmental regulations to ensure regulatory compliance.

Conclusions

1. NORM contamination can be expected at nearly every petroleum facility.

2. The presence of NORM in oil and gas production facilities, gas processing plants, pipelines, and other petroleum equipment and facilities is not, in general, a serious technical problem.

3. The concentrations of NORM contamination and the energies of the radiation are relatively low and do not usually present a health hazard to the public or to most personnel in the industry. Some facilities may be more highly contaminated, however, and may be hazardous to maintenance personnel in particular.

4. Radium contamination of pipe scale can be a serious problem requiring special procedures for the removal and disposal of contaminated scale to prevent contamination of personnel and the environment.

5. Produced water may be contaminated with radium, requiring special procedures for the protection of the environment.

6. Surface equipment and facilities at production sites also may be contaminated with NORM, requiring special repair and maintenance procedures and the disposal of NORM-contaminated wastes.

7. The buildup of long-lived radon decay products (specifically lead-210) in gas pipelines, gasoline plants, and refineries requires that specific procedures be implemented for inspection and maintenance personnel to ensure their safety when working on the internal parts of equipment and facilities where radon may have been present.

8. A serious problem that must be addressed is the disposal of radioactive materials and equipment. Options available for the disposal of NORM and NORM-contaminated wastes are limited.

9. Although only Louisiana and Mississippi have enacted regulations for the control of NORM, Texas will have regulations early in 1993, and other states and Canada can be expected to enact similar legislation. The U.S. EPA is considering enacting NORM regulations on the federal level.

10. The industry must comply with the regulations.

Although potentially hazardous to personnel and the environment, NORM contamination is controllable.

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SI Metric Conversion Factors

curie × 3.7*	E+10 = Bq
°F (°F-32)/1.8	= °C
ft × 3.048*	E-01 = m
ft ³ × 2.831 685	E-02 = m ³
R × 2.58	E-04 = C/kg

*Conversion factor is exact.

Provenance

Original SPE manuscript, **NORM Contamination in the Petroleum Industry**, received for review Oct. 6, 1991. Revised manuscript received Oct. 29, 1992. Paper accepted for publication Jan. 15, 1992. Paper (SPE 22880) first presented at the 1991 SPE Annual Technical Conference and Exhibition held in Dallas, Oct. 6-9.

JPT

103535

An Analysis of the Impact of the Regulation of
"Radionuclides" as a Hazardous Air Pollutant on
the Petroleum Industry

Prepared for the Committee for Environmental Biology and
Community Health, Department of
Medicine and Biology, American Petroleum Institute

October 19, 1982

Executive Summary

The impact of regulating "Radionuclides" as a hazardous air pollutant under Section 112 of the Clean Air Act is examined and is found to depend upon what is defined as an "acceptable level" of risk, and whether the regulation will be based upon committed dose equivalent to the general public, source characteristics, or individual radioisotopes.

Almost all materials of interest and use to the petroleum industry contain measurable quantities of radionuclides that reside finally in process equipment, product streams, or waste. In addition, groundwater used for waterflood and brine solutions from operating wells contain biologically significant quantities of Radium 226 and Radon 222. The mining, cleaning, and combustion of coal also add measurably to the burden of radioactive pollutants in ambient air.

Listing radionuclides as a hazardous air pollutant also brought radionuclides under the umbrella of CERCLA. Again, the impact of defining a "reportable quantity" depends upon the definition of "acceptable risk" and whether the standard is based upon a committed dose equivalent to a member of the general public or is established isotope by isotope.

Table 10 in the main body of the report summarizes the quantities of radionuclides found in products and raw materials of most concern to API member companies. Table 13 summarizes the EPA's estimate of risk associated with certain industry operations to a maximum exposed individual inhaling and ingesting radionuclides from products of combustions. Table 17 shows how the impact upon the industry expands as the level of acceptable risk is reduced, and Table 18 summarizes the combined potential impact of regulations under both the Clean Air Act and CERCLA.

It is concluded that the regulation of radionuclides could impose a severe burden on API member companies, and it would be prudent to monitor closely both regulatory actions.

What Radionuclides Should Be of Concern?

When the EPA listed "RADIONUCLIDES" as a hazardous air pollutant, they meant all radioactive materials without exemption for material concentration (specific activity), quantity, or material with which it is associated. There were no exemptions for the non-nuclear industries.

The general classification "Radionuclides" includes:

- By-Product Material - the material made radioactive through the use of special nuclear material or bombardment by radiations resulting from the use of special nuclear material (CFR, 1982).
- Special Nuclear Material - the fuel for reactors.
- Source Material - essentially the concentrated elements from which special nuclear material is separated.
- Naturally Occurring or Accelerator-Produced Radioactive Materials - those radioactive materials found in nature or made radioactive in a laboratory by an energetic ion beam. These are the materials that are present in our products in minute amounts.

While many petroleum companies use radioactive materials as tracers and in process control, these are carefully regulated by the U.S. Nuclear Regulatory Commission present little, if any, environmental hazard, and are of small concern. The API should be more concerned with the potential for naturally occurring radionuclides being in our raw materials. Naturally occurring radioactive material is either produced in the earth's atmosphere as a result of cosmic-ray bombardment, i.e. Carbon-14, or exists as primordial radionuclides, i.e. radionuclides present from the event of creation in the earth's crust, such as Potassium 40 and Uranium. The families of radionuclides or series of radionuclides that are of most significance are in this primordial grouping. These are the decay series of Uranium 238, Uranium 235, Thorium 232. Uranium 235 is the nuclear fuel. About 0.7% of natural uranium is Uranium 235. Uranium 238 and Thorium 232 are uniformly distributed in the earth's crust.

The Uranium 238 (Figure 1) series can be divided into some four subseries, all possessing significant exposure potential to man. These subseries are the decay of Uranium 238 and Uranium 234 to Thorium 230, the decay of Thorium 230 to Radium 226, the decay of the inert gas Radon 222 and its short-lived daughters to the long-lived daughter, product Lead 210, and finally the decay of Lead 210 to stable lead (NCRP, 1975). The elements in the Subseries Uranium 238 to Thorium 230 represent significant sources of internal exposure, primarily in the occupational environment. Radium 226 is a potent source of radiation exposure, both internal and external. Radon 222 and its short-lived progeny deliver significant population and occupational exposures to the upper tracheobronchial tree, while Lead 210 and its decay product contaminate much process equipment and can represent significant exposure to the bone in some occupational subgroups. Radon 222 and its daughters cause the most severe impact to the public health.

The Thorium series (see Figure 2) is characterized by the long-lived Thorium 232 at the head of the series and decay products that are relatively short lived. If no migration of the series members takes place, radio-equilibrium is established in about 60 years. In minerals and rocks of low permeability, the thorium series radionuclides are expected to be in equilibrium. In soils, natural waters, natural gas, crude oil and the atmosphere, the disparate chemical and physical properties of the series tend to cause disequilibrium. Certain parts of the world, Kerala in India and monazite mining districts in Brazil, are famous because of their high background levels of external radiation from the thorium series.

The Presence of Radionuclides in Crude Oil,
Natural Gas (NG), Liquefied Petroleum Gas (LPG),
Coal, Phosphate Rock, and Groundwater

It is well known that some naturally occurring elements, uranium for example, have an affinity for crude oil. The uranium that accumulates in crude oil, oil shale, coal, and phosphate rock is the residue remaining after the marine deposits have been consolidated. Petroleum is often assumed to have migrated to a position of minimum hydraulic potential in a "reservoir rock", which may or may not be derived from the same source deposits as the petroleum. Associated with the petroleum in widely ranging proportions are brine and natural gas. The radionuclides, particularly those of the uranium series (see Figure 1), distribute themselves among the three fluid phases and the crusty, solid lining of the intergranular spaces according to chemical affinity, sorption phenomena and the vagaries of radioactive recoil. The gaseous radon isotopes follow the temperature-pressure dependent Henry's Law in their partitioning among the gas and liquid phases. The sites of major uranium-series nuclides in the Texas Panhandle gas field and adjacent areas have been studied extensively (Pierce, 1964). In the gas reservoir, uranium is resident mainly in the crude oil and in pellets of solid hydrocarbon, radium is found in the brine and in the solid crust, and radon distributes itself among the oil, gas and brine in that order. The series equilibrium is evidently disrupted continually by movement of decay products from one phase to another that is chemically or physically more compatible.

Crude Oil

Very little has appeared in the literature concerning the levels of radioactivity in crude oil, but it would be safe to assume that the actual levels of contamination would be between that found in coal and that found in sedimentary rock similar to that of the reservoir rock or where the petroleum was formed. Uranium in the earth's crust averages 4 parts per million (CRC, 1969). The NCRP (NCRP, 1975) reported the data shown in Table 1 for the various rock types.

TABLE 1 - Summary of concentrations of major radionuclides in major rock types and soils

Rock Type	Potassium-40		Rubidium-87		Thorium-232		Uranium-238	
	percent total Potassium	pCi/g	ppm total Rubidium	pCi/g	ppm	pCi/g ^b	ppm	pCi/g ^c
Igneous Rocks								
Basalt (Crustal average)	0.8	7	40	0.9	3-4	0.3-0.4	0.8-1	0.2-0.3
Mafic ^d	0.2-1.1	2-9	10-50	0.2-1	1.6, 2.7	0.2, 0.3	0.5, 0.9	0.2, 0.3
Salic ^d	4-3	30-40	170-200	4-8	14, 20	1.7, 3.3	3.9, 4.7	1.3, 1.6
Granite (Crustal average)	>4	>20	170-200	4-8	17	1.9	3	1
Sedimentary Rocks								
Shale	2.7	22	120 ^e	3	13	1.5	3.7	1
Sandstones:								
clean quartz	<1	<4	<90 ^e	<1	<2	<0.3	<1	<0.3
dirty quartz	27	107	507	27	3-67	0.3-0.77	3-37	17
arkose	2-3	18-24	80-120 ^e	2	27	0.27	1-27	0.3-0.77
Beach sands (unconsolidated)	<1	<37	<907	<17	6	0.7	2	1
Carbonate Rocks	0.2	2	10 ^e	0.2	2	0.2	2	0.7
Soils ^f	1.3	12	85 ^e	1.4	9	1	1.8	0.6

^a References cited in text unless otherwise noted; single values are averages; values estimated in absence of references are followed by question mark.

^b To obtain series equilibrium alpha, beta, or approximate gamma (excluding bremsstrahlung and x radiation) activity, multiply by 4, 4, or 3 respectively.

^c To obtain series equilibrium alpha, beta, or approximate gamma (excluding bremsstrahlung and x radiation) activity, multiply by 3, 4, or 3, respectively.

^d From Clark et al. (1966); for potassium and rubidium, the range of values for rocks within the class is given; for thorium and uranium, the median and mean value are given, respectively.

^e Estimated by application of crustal abundance ratios with respect to potassium.

^f In-situ gamma-spectral measurements at 200 locations by Lowder et al. (1944).

Table 2 (UNSCEAR, 1977) shows additional data.

TABLE 2. TYPICAL ACTIVITY CONCENTRATION OF ⁴⁰K, ²³⁸U AND ²³²Th IN COMMON ROCKS AND ESTIMATED ABSORBED DOSE RATE IN AIR 1 m ABOVE THE SURFACE

Type of rock	Typical activity concentration (pCi g ⁻¹)			Absorbed dose rate in air (μrad h ⁻¹)
	⁴⁰ K	²³⁸ U	²³² Th	
Igneous				
Acidic (e.g. granite)	27	1.6	2.2	12
Intermediate (e.g. diorite)	19	0.62	0.88	6.2
Mafic (e.g. basalt)	6.5	0.31	0.30	2.3
Ultrabasic (e.g. durite)	4.0	0.01	0.66	2.3
Sedimentary				
Limestone	2.4	0.75	0.19	2.0
Carbonate	-	0.72	0.21	1.7
Sandstone	10	0.5	0.3	3.2
Shale	19	1.2	1.2	7.9

Source: References 1, 353.

Gulf (Rhodes, 1972) has measured the amount of Lead 210 - a Uranium 238 daughter product - in light hydrocarbon streams. Their finding suggests concentrations as high as 1.2 ± 0.9 pCi g^{-1} in such streams.

Natural Gas

The quantities of radon contained in the natural gas of the Panhandle Field and at all other gas fields sampled for radon is of significance to radiation exposure estimates for the U.S. general population. Natural gas of the Panhandle field was found to contain an average radon concentration of about 100 pico curies per liter (pCi/l). Maximum concentration as much as 1450 pCi/l were observed after expansion to atmospheric pressure (Pierce, 1964). In-transit decay, processing of gas for pipelines, and storage decrease the radon contamination, but increase daughter (decay) product, i.e. Lead-210 (see Figure 1), contamination of lines, processing equipment, and storage tanks. This contamination can produce significant occupational exposures. Radon concentrations found in natural gas are summarized in Tables 3 and 4 (UNSCEAR, 1977).

TABLE 3. RADON CONCENTRATION IN NATURAL GAS AT THE WELL

Location of well	Radon concentration (pCi l ⁻¹)		Reference
	Average	Range	
Borneo			
Ampa field	...	1.5-3.2	352
Canada			
Alberta	62	10-205	
British Columbia	473	390-540	302
Ontario	169	4-800	
Germany, Federal Rep. of	...	1.0-9.6	352
Netherlands			
Sinchteron	...	1.1-2.8	
Other fields	...	3.7-44.7	352
Nigeria			
Niger delta	...	0.9-2.9	352
North Sea			
Leman field	...	2.0-3.8	
Indefatigable field	1.8	...	352
United States			
Colorado, New Mexico	25	0.2-160	
Texas, Kansas, Oklahoma	< 100	5-1450	
Texas Panhandle	...	10-520	
Colorado	25.4	11-45	
Project Gasbuggy area	15.8	...	
California	...	1-100	171
Kansas	100	...	
Wyoming	10	...	
Gulf Coast (Louisiana, Texas)	5	...	
California, Louisiana, Oklahoma, Texas	...	1-120	98

TABLE 4. RADON CONCENTRATION IN NATURAL GAS IN THE DISTRIBUTION LINE

Area	Radon concentration (pCi l ⁻¹)	
	Average	Range
Poland (Warsaw)	8	4-14
United States		
Chicago	14.4	2.3-31.3
New York City	1.5	0.5-3.8
Denver	50.5	1.2-119
West coast	15	1-100
Colorado	25	6.5-43
Nevada	8	5.8-10.4
New Mexico	45	10-53
Houston	8	1.4-14.3

Sources: Poland, 359; United States, 171.

Table 5 summarizes data from the USEPA.

Table 5. Radon-222 concentrations in natural gas at production wells

Area	Radon-222 level, pCi/l		Reference
	Average	Range	
Colorado			
New Mexico	25	0.2-160	1
Texas, Kansas, Oklahoma	<100	5-1450	2
Texas Panhandle	---	10-520	3
Colorado	25.4	11-45	5-7
Project Gasbuggy Area	15.8-19.4	-----	7
Project Gasbuggy Area	29.4	12-59	8
California	---	1-100	10
Gulf Coast (Louisiana, Texas)	5	-----	11
Kansas	100	-----	11
Wyoming	10	-----	11
Overall average	37		

Liquefied Petroleum Gas

When natural gas is thermally fractionated to recover the heavier hydrocarbons, the radon tends to concentrate in the ethane and propane fractions (Gessell, 1975). These are sold in mixtures sometimes including butane, as liquefied petroleum gas (LPG) for use as a fuel. Typically, the concentration of Radon 222 in LPG is eight times the concentration in the natural gas before processing (Gessell, 1974). Subsequent storage allows the Radon 222 to decay, however, and there are indications that despite the higher initial Radon 222 concentration, LPG is no more important than natural gas as a pathway for population exposures to Radon 222.

An occupational external exposure situation can occur in gas processing plants where daughters of Radon 222 collect on the inside of processing equipment, especially pumps, and also create some disposal problems (Gessell, 1974).

Coal

Coal and its residues appear to be significantly contaminated with Radium 226. Table 6 (USCEAR, 1977) shows that U.S.-mined coal contains biologically significant quantities of Uranium 238, Radium 226, Bismuth 214, Thorium 228 and Thorium 232. Barber (Barber, 1977) also reported significant concentrations of Bismuth 214, Potassium 40 and Thallium 208. The U.S. Geological Survey Service (USCGS, 1959) has reported uranium concentrations in coal up to 0.2%.

TABLE 6. ACTIVITY CONCENTRATION OF RADIONUCLIDES IN COAL AND COAL RESIDUES
(pCi g⁻¹)

Type of coal or coal residue and its origin	⁴⁰ K	²³⁸ U	²²⁶ Ra	²¹⁰ Pb	²¹⁰ Rn	²²⁸ Th	²³² Th	Reference
Coal								
Australia			0.8-1.3					23
Czechoslovakia (brown)			0.11, 0.35					165
Germany, Fed. Rep. of	< 2.5		< 0.7				< 0.6	307a
Hungary (bituminous)			0.04					165
Poland (bituminous)			0.048-0.94					165
Poland (brown)			0.90					165
United States								
Illinois	2.5		0.6 ^a			0.04 ^b		20
Montana	0.7		0.3 ^a			0.07 ^b		20
North Dakota	2.2		0.2 ^a			0.02		20
United States		0.7					0.2	185
United States			0.014	0.28 ^c				175
Coal ash (laboratory processing)								
Australia			4.7-8.3					23
Germany, Fed. Rep. of			6.2 ^c			2.6		172
Japan	19		5.8				3.4	307a
Central			0.10	19.8	1.15	15.3		257
Southern			0.98	8.16	0.46	2.35		257
Northern			0.63	105.0	1.45	6.79		257
United States (semi-bituminous)			3.8		2.4	2.6		79
Slag								
Poland	17.3		4.3 ^a			1.2 ^b		272
United States	26		4.5 ^a			0.5 ^b		20
United States		4.9					1.5	185
United States			0.55	1.0				175
Fly ash								
Australia			14.0					23
Hungary			0.6-15					204
Poland			1.0					165
Poland	22.5		6.4 ^a			1.1 ^b		272
Poland (bituminous)		1.5, 2.8	0.61, 4.18	4.4, 6.7			0.18, 0.22	166
Poland (lignite)			0.91					166
United States		10					2.6	185
United States			0.4	17.3				175
United States	11		3.1 ^a			0.4 ^b		20

^a Assumed equal to activity concentration of ²¹⁴Bi.

^b Assumed equal to activity concentration of ²¹⁰Pb.

^c Including activity concentration of ²²⁶Ra.

Solvent Refined Coal

Hittman Associates (USDC, 1978) have analyzed solvent refined coal for radionuclides in 1970 and noted concentration of uranium in the SRC particulates. These data are summarized in Table 7.

TABLE 7. RADIONUCLIDE CONCENTRATIONS
(ppm by weight)

Source	Uranium	Thorium
<u>Coal</u>		
Sample #1	1.3	4.74
Sample #2	1.4	4.24
<u>SRC</u>		
Sample #1	0.8	4.99
Sample #2	1.3	3.73
<u>Coal Particulates</u>		
Sample #1	2.6	14.99
Sample #2	1.9	20.50
<u>SRC Particulates</u>		
Sample #1	39	11.46
Sample #2	28	9.48

Phosphate Rock

Many of the American Petroleum Institute's members are also engaged in the peripheral activity of mining phosphate rock and manufacturing fertilizer. Table 8 (UNSCEAR, 1977) summarizes the presence of radioactivity of the rock and its products.

TABLE 8. ACTIVITY CONCENTRATION OF ^{226}Ra , ^{238}U , AND ^{232}Th IN PHOSPHATE ROCK AND IN PRODUCTS DERIVED FROM IT
Marketable rock produced in Florida (United States)

Sample	Production in the United States in 1973 ^a (10 ⁶ t)		Activity concentration (pCi g ⁻¹)		
	Amount	P ₂ O ₅ content	^{226}Ra	^{238}U	^{232}Th
Marketable rock	38	—	42	41	0.4
<i>Wet process products</i>					
Normal superphosphate	3.1	0.6	25	^b	—
Triple superphosphate	3.4	1.6	21	57	0.4
Ammonium phosphate	5.3	2.4	5.7	63	0.4
Phosphoric acid	10.0	5.1	0.6	—	—
Gypsum	23.0	—	3.3	6.1	0.3
<i>Electric furnace process products</i>					
Slag	—	—	56 ^c	—	—

Source: Reference 109.

^aFlorida accounts for 82 per cent of the marketable rock production of the United States.

^bThe activity concentration of ^{238}U in normal superphosphate is expected to be equal to that of ^{226}Ra .

^cThe ^{226}Ra activity concentration in the input feed ore was 60 pCi g⁻¹.

Groundwater

In groundwaters, such as those used for waterflood operations, Radon 222 is usually present in a concentration range of from several hundred to several thousand pico curies per liter. In North Carolina, where the geology is primarily sedimentary, Radon concentrations vary from 20 to 47,000 pCi/l. Approximately 33% of supplies tested had concentrations greater than 2000 pCi/l (Sasser, 1978).

The groundwaters around Houston are probably typical of those associated with most petroleum operations. The radon concentrations shown in Table 9 (Prichard, 1981) are for water as it is delivered to Houston homeowners for consumption. In-ground levels are probably similar to the higher samples in North Carolina.

Table 9
 Radon in Houston Homeowners' Water Supplies from
 Groundwater Sources (Prichard, 1981)

<u>Tracts Included</u>	<u>Average Con- centration of Radon (pCi/L)</u>
All	437
Tracts with Concentration greater than 500 pCi/l	853
Tracts with Concentrations greater than 1000 pCi/l	1722

Summary

Table 10 estimates the amounts of radioactivity contained in petroleum products in more familiar units. If we assume that a refinery processes one million barrels of crude per day, we find that we have handled some 1.46 curies per day or 533 curies per year of radioactivity, mostly in the form of naturally occurring Potassium 40.

If it is correct to assume that the uranium in the oil is at the same concentration as the host rock, then a one-million-per-day-capacity refinery could be throughputting some 480 lb of uranium per day (177,200 lb uranium per year).

TABLE 10

Quantities of Radionuclides in Normal Measurement Units Used by the Petroleum Industry

Item/Product	Units	Radioactive Contaminant							Total
		⁴⁰ K	²³⁸ U	²²⁶ Ra	²¹⁰ Pb	²³² Th	²²² Rn		
Crude Oil*	uCi/BBL	1.4	0.07		0.17	.04			1.46
Kuwait Oil	uCi/BBL				0.17				0.17
Natural Gas**	uCi/10 ⁶ ft ³						1400		1400
LPG	uCi/10 ⁶ ft ³						1400		1400
Coal-US	uCi/T	23.6	4.5	4.0	0.9	1.3	—		30.3
SRC-Product	uCi/T		0.6			100			100.6
Shale Oil	uCi/BBL	2.8	.17			.17			3.14
Shale Waste	uCi/T	17	1.0			1.0			.19
Phosphate Rock (Marketable)	uCi/T		38	38		.36			76.36
Ground Waters	uCi/1,000 gal.						1.6		1.6

* Assumes Uranium in Oil is equal to Uranium in host Rock

** Assumes Average Concentration of 50pCi/l

Note: The USNRC regulates microcurie amounts of radioactive materials that are not naturally occurring.

Potential Public Health Effects of the Use of
Materials and Products Important to
the API and Its Member Companies

There are probably as many estimates of impact of radionuclides in air as there are individuals capable and incapable of making such estimates. Whether or not a radioactive material contained in petroleum, natural gas, or coal, is taken into the body depends upon a number of factors, including:

- amount originally present
- amount made airborne
- atmospheric phenomena and transport
- plate out and rain out
- routes of entry
- amount retained
- clearance mechanisms
- dietary sources
- dose contribution of "infinite cloud"
and "infinite plane"
- and others

The EPA method of analysis assumed certain source characteristics and target populations (EPA, 1979), used a Gaussian computer model to disperse the radioactive materials (BAES, 1981) and a second computer program to model intake, dose, and dose response based upon the linear non-threshold model (Begovich, 1981), (Sullivan, 1981), (Dunning, 1981). The first analysis by EPA concerning the naturally occurring radioactive materials is shown in Table 11 (EPA, 1979). Table 12 is a later analysis, currently in draft form, that expanded the original list (Teknekron, 1981).

Analysis of the data in both reports suggests that API companies should be concerned with operations described in Table 13. Table 13 suggests that the radioactive material emissions having the greatest potential impact on API member companies are Radon-222, followed closely by Uranium-238 and Radium-226. The two EPA analyses demonstrate that any operation involving the combustion of fossil fuels or the preparation of such fuels for use could be subject to regulation under the Clean Air Act.

Table 1.1. Summary of radiological impact caused by atmospheric emissions of natural radioactive materials

Source category	Number of sources	Principal radionuclide emissions (Ci/yr)	Exposure levels		Principal dose equivalent rates		Life-time risk to the maximum individual (x 10 ⁻⁶)	Expected fatal cancers per year of operation
			Maximum individual (mSv)	Regional Population (Person-dL)	Maximum individual (mrem/yr)	Regional Population (Person-rem/yr)		
Uranium Mines (4.1)								
Underground	251	Rn-222 6700	0.006	1.3	-	10,000	0.03	0.03
Open pit	36	Rn-222 2000	0.0008	0.4	-	1,000	0.008	0.02
Uranium Mills (4.2)	20	Rn-222 2700 U-238/d 0.4	0.005	0.5	Lung 350 Bone 360	10,000	0.01	0.03
Phosphate Industry (4.3)								
Mining and beneficiation	35	Rn-222 1300	0.0002	4.9	-	300	0.1	
Drying and grinding facilities	20	Rn-222 20 U-238/d 0.03	0.00005	0.08	Lung 54 Bone 79	500	0.004	
Phosphoric acid plant	35	Rn-222 480 U-238/d 0.1	0.0007	2.0	Lung 85 Bone 110	2,000	0.05	
Elemental phosphorus plant	9	Rn-222 490 U-238/d 0.15 Po-210 7.4	0.0004	2.0	Lung 740 Bone 570 Kidney 1800	6,000	0.1	
Coal-fired power stations ^d (4.4)								
New stations	145	Rn-222 1.9 U-238/d 0.3 Th-232/d 0.07	<0.00001	<0.00001-0.024	Lung Bone	0.8-2.1 1.6-16	0.5-2600 1.5-1300	10-50 0.00008-0.2
Existing stations	250	Rn-222 0.7 U-238/d 0.8 Th-232/d 0.3	<0.00001	<0.00001-0.013	Lung Bone	6.7-15 8.3-62	2.7-19,000 7.1-11,000	60-700 0.0004-1.5

See footnotes at end of table.

Table 11. Summary of radiological impact caused by atmospheric emissions of natural radioactive materials--continued

Source category	Number of sources	Principal radionuclide emissions (Ci/yr) ^a	Exposure levels		Principal dose equivalent rates Maximum Individual Population (mrem/yr) (Person-rem/yr)	LifETIME risk to the maximum individual (x 10 ⁻⁶)	Expected fatal cancers per year of operation Regional U.S. (fatal cancers)
			Maximum Individual (ML)	Regional Population (Person-ML)			
Metal mining and milling ^b (4.5)	177	Rn-222 17 to 3000	<0.00001 to 0.001	0.005 to 0.8	-	20 to 2000	0.0001 to 0.02
Nonmetal mining and milling ^c (4.5)	1,200	Rn-222 0.2 to 18	<0.00001 to 0.00004	0.0007 to 0.06	-	0.7 to 50	0.00002 to 0.001
Geothermal power site (4.6A)	1	Rn-222 540	0.0004	1.5	-	700	0.03
Ground water treatment plants (4.6B)	40,000	Rn-222 3.4	<0.00001	0.06	-	10	0.001

^aU-238-d emission rates are the sum of the individual release rates for uranium-238, and its daughter products uranium-234, thorium-230, radium-226, lead-210, and polonium-210. (For elemental phosphorus plants only, polonium-210 is not included in this sum.)
^bTh-232-d emission rates are the sum of the individual release rates for thorium-232 and its daughter products radium-228, thorium-228, and radium-224.

^cThe maximum dose equivalent rate an individual is likely to receive living near the facility.
^dThe maximum collective dose equivalent rate to the regional population. This is the maximum value expected to occur within 100 years following the start of facility operation.
^eChanges of impact values represent variations due to station siting.
^fIncludes iron, copper, zinc, and bauxite.
^gIncludes clay, limestone, fluor spar.

Table 12

SUMMARY OF RISKS FROM SOURCES OF AIRBORNE EMISSIONS OF RADIONUCLIDES

Source Category	Principal Radionuclide Emissions (Ci/yr)	Dose Equivalent Rates		Radon Daughter Exposure		Health Effects	
		Maximum Exposed Individual (air/cm ³ ·rem/yr)	Collective Exposed (person·rem/yr)	Maximum Individual (working level)	Regional Population (person working level)	Lifetime Risk to the Maximum Exposed Individual	Expected Fatal Concerns per Year of Operation to the Population at Risk
Ground Water Treatment Plant (3.1) Southeastern Site	Rn-222 B.1	Lung 5.7E-3 Bone 1.9E-4	2.9E-2 9.3E-4	3.8E-4	1.9E-2	6E-6	5E-4
	Rn-222 B.1	Lung 9.6E-3 Bone 3.1E-4	0.15 4.9E-3	6.4E-5	0.10	1E-5	2E-3
Geothermal Power Plant (3.2)	Kr-222 5.5E+2	Lung 1.22	3.1	8.1E-4	2.1	1E-3	5E-2
	Rn-222 2.1E+1 U-238 1.8E-2	Lung 3.5E+1 Bone 5.8E+1	8.8E+1 2.4E+2	9.7E-6	5.0E-2	1E-4	7E-3
Phosphate (3.3) Phosphate Mine:	Rn-222 2.6E+3 U-238 4.0E-3	Lung 1.7 Bone 5.5	9.2 0.3	5.9E-4	3.2	1E-3	2E-2
	Rn-222 6.5E+1 Ra-226 1.8E-2 U-238 3.5E-2	Lung 6.4E+1 Bone 1.0E+2	1.5E+2 3.5E+2	3.1E-5	0.16	2E-4	1E-2
Elemental Phosphorus Plant: Stack	Kr-222 3.2E+2	Lung 0.22	1.1	1.4E-4	0.75	3E-4	2E-2
	U-238 2.2E-2 Ra-226 7.0E-3 Pb-210 3.3E-2 Po-210 3.2E+0	Lung 2.1E+2 Liver 1.7E+1 Bone 7.0E+1	5.0E+2 2.6E+2 2.5E+2	7E-4		7E-4	4E-2
Area Source	Kr-222 2.2E+2	Lung 0.15	0.78	1.0E-4	4.3E-2	2E-4	4E-2
	Rn-222 2.1E+2 U-238 2.3E-5	Lung 0.52 Bone 0.21	3.0E-2 7.2E-3	2.7E-4	1.8E-2	4E-4	4E-4
Non-ferrous Metal Mining, Milling, Processing (3.4) Underground Mine, Area Source #1	Rn-222 2.3E+2 U-238 1.0E-2	Lung 4.1E+1 Bone 6.7E+1	1.2 2.8	2.3E-4	2.0E-2	5E-4	5E-4
	Kr-222 4.5E+3 U-238 5.0E-2	Lung 3.9E+1 Bone 5.7E+1	8.8 6.1	7.2E-4	0.15	1E-3	4E-3
Open-Pit Mine Copper Dr., Mill	Rn-222 1.7E+3 U-238 2.0E-2	Lung 7.3E+1 Bone 1.2E+2	6.5 1.6E+1	1.6E-3	0.38	3E-3	1E-2

16

Table 12 (Cont.)
SUMMARY OF RISKS FROM SOURCES OF AIRBORNE EMISSIONS OF RADIONUCLIDES

Source Category	Principal Radionuclide Emissions (Ci/yr)	Dose Equivalent Rates	Radon Daughter Exposure	Health Effects
Non-Uranium Mining, Milling, Processing (Cont) Metal Smelter: Main Stack	Ki-222 8.0	Lung 5.3E+1 Liver 1.6E+1 Bone 3.7E+1	Negligible	2E-4
	Pu-210 1.0E+1	2.4E+1		
	Pu-210 1.0E+1 U-NaL 4.5E-2	4.0E+1		
Area Source	Ki-222 1.7E+2 U-NaL 5.3E-2	Lung 2.0E+2 Red Marrow 2.3E+1 Bone 3.2E+2	1.5E-4	6E-4
	Ra-222 4.3E-1 U-NaL 2.8E-4	Lung 2.0E+1 Liver 1.8 Bone 2.6	Negligible	7E-5
Area Source	Ki-222 4.3E-1 U-NaL 5.1E-6	Lung 0.79 Bone 4.6E-2	1.4E-6	4E-6
Lead Mining and Cleaning (3.6) Underground Mine	Ki-222 1.6E+1 U-230 3.4E-6	Lung 2.6E-2 Red Marrow 1.6E-2 Bone 3.1E-2	Negligible	9E-3
	Th-232 3.5E-6	2.2		
	Ki-222 1.4E+0 U-238 3.6E-4 Th-232 2.8E-4	2.2 3.3 2.3E+1 6.4E+1		
Strip Mill	Ki-222 0.17 U-238 2.2E-4 Th-232 2.2E-4	Lung 0.27 bone 0.69	Negligible	1E-3
Coal Cleaning Plant	Ki-222 2.4 Ra-222 6.7E-2	Lung 2.9E-1 Lung 5.2E-1	1.9E-7 3.5E-6	3E-6 4E-6
Natural Gas Compression Units (3.7) Natural Gas Boiler Natural Gas Turbine		Lung 4.5E-2 Lung 1.3E-2	3.0E-2 8.8E-2	6E-4 2E-4

Table 12 (Cont.)
SUMMARY OF RISKS FROM SOURCES OF AIRBORNE EMISSIONS OF RADIONUCLIDES

Source Category	Principal Radionuclide Emissions (Ci/yr)	Dose Equivalent Rates		Radon Daughter Exposure		Health Effects	
		Maximum Exposed Individual (mrem/yr)	Collective (person-rems/yr)	Maximum Individual (working level)	Regional Population (person working level)	Lifetime Risk to the Maximum Exposed Individual	Expected Fatal Cancers per Year of Operation to the Population at Risk
Coke Production (3.8) Northeastern Site	Ku-222 1.9E+0	Lung 1.8E+1	5.7E+2	Negligible	6E-5	3E-2	
	Th-232 1.1E-3	Bone 4.3	1.9E+2				
	Po-210 6.2E-1						
	U-238 1.1E-3						
Midwestern Site	Ku-222 1.9E+0	Lung 1.9E+1	3.6E+1	Negligible	1E-6	3E-3	
	Th-232 1.1E-3	Liver 2.1	2.8E+1				
	Po-210 6.2E-1	Bone 5.9	1.7E+1				
	U-238 1.1E-3						
Coal-fired Steam Electric Generating Stations (3.9) New CPSEGS: Midwestern Site	U-238 2.0E-2	Bone 4.2	2.9E+2	Negligible	5E-5	3E-3	
	U-235 1.2E-3						
	Th-232 7.3E-3						
	U-238 2.0E-2	Bone 1.3E+1	2.2E+1				
	U-235 1.2E-3						
	Th-232 7.3E-3						
Southeastern Site	U-238 2.9E-2	Bone 1.2E+1	7.4E+2	Negligible	9E-5	1E-2	
	U-235 1.6E-3						
	Th-232 2.1E-2						
Existing CPSEGS: Midwestern Site	U-238 2.9E-2	Bone 3.1E+1	4.9E+1	Negligible	5E-5	5E-4	
	U-235 2.1E-2						
	Th-232 2.1E-2						
Southeastern Site	U-238 2.9E-2	Lung 7.4	2.3E+2	Negligible	3E-5	2E-2	
	U-235 2.1E-2	Bone 1.0E+1	6.2E+2				
	Th-232 3.3E-3						
Coal-fired Industrial boilers (3.10) Eastern Site	U-238 4.5E-3	Lung 8.0	1.5E+1	Negligible	3E-5	1E-3	
	U-235 2.6E-4	Bone 2.2E+1	5.2E+1				
	Th-232 3.3E-3						
Midwestern Site	U-238 4.5E-3			Negligible	3E-5	1E-3	
	U-235 2.6E-4						
	Th-232 3.3E-3						

TABLE 13

Summary of Operations Whose Regulation Will Impact On API Member Companies

Operation	Isotope of Interest	Lifetime Risk to the Maximum Exposed Individual
Ground Water Treatment Southeastern Site	²²² Rn	6×10^{-4}
	²²² Rn	1×10^{-3}
Southwestern Site	²²² Rn	1×10^{-3}
Geothermal Power	²²² Rn	6×10^{-4}
	²²² Th	
Coke Production Northeast	²¹⁰ Pu	
	²³⁸ U	
	ditto	1×10^{-4}
Southeastern	²³⁵ U	5×10^{-3}
Coal Fired Steam New Midwestern	²³⁵ U	5×10^{-3}
	²³² Th	
	ditto	3×10^{-3}
	ditto	3×10^{-3}
Southeastern Existing Coal Fire Industrial Boilers	²²² Rn	9×10^{-3}
	²³⁵ U	
Eastern	²³² Th	5×10^{-4}
Midwestern	ditto	1×10^{-4}
Coal Mining and Cleaning Underground Mining	²²² Rn	3×10^{-4}
	²³⁵ U	4×10^{-4}
Strip Mining	²³² Th	5×10^{-4}
Coal Cleaning	ditto	1×10^{-4}
Natural Gas Combustion	²²² Rn	3×10^{-4}
Natural Gas Turbine	²²² Rn	4×10^{-4}

Regulatory Options and Their Implications

As far as industry is concerned, the regulatory issues should be:

1. What is an "acceptable level of risk"?
2. Which approach will be followed in setting the standard, a generic "committed" dose equivalent approach or regulation isotope by isotope?

The EPA risk assessment in part evaluated the risk to a "maximum exposed individual". The risk to this person from sources of interest to the API ranged from 9×10^{-3} (underground coal mining) to 1×10^{-6} (coal cleaning). Risks for this individual resulting from the combustion of fossil fuels ranged in the 5×10^{-5} area (Ieknekron, 1981). Table 14 (Wilson, 1981) gives an indication of how those risks compare with others "accepted" by United States residents.

The federal bureaucracy also has been pondering over the concept of acceptable and de minimis risk. Dr. Roy Albert has been supporting 1×10^{-5} excess lifetime risk of fatal cancer in the drinking water area. The FDA has accepted 1×10^{-6} excess risk as acceptable for acrylonitrile migration in food containers. The USNRC is considering in staff discussions 1×10^{-4} excess lifetime risk of death from occupational exposure and 1×10^{-6} excess lifetime risk of death or lower as de minimis. The EPA assessment lists the combustion of fossil fuels as lying between 10^{-4} and 10^{-5} .

In addition to the definition of acceptable risk, the method of setting the limits could have considerable impact. There are two methods available to the EPA: regulate population-committed dose equivalent to air pollutants, the generic approach; or limit the emission of specific radionuclides.

The generic approach specifies that the emissions of radionuclides will be controlled to a level such that the total committed dose equivalent received by an individual does not produce a risk of fatal cancer exceeding that of a preselected whole-body dose commitment (ICRP, 1977; ICRP, 1980).

Mathematically, this can be expressed as

$$\frac{H_d}{D} + \sum_j \frac{I_{i,j}}{(ALI)_{i,j}} + \sum_j \frac{I_{o,j}}{(ALI)_{o,j}} \leq 1$$

where H_d is the deep dose commitment or (whole body dose)

$I_{i,j}$ is the annual intake of radionuclide
j by inhalation

$I_{o,j}$ is the annual intake of radionuclide
j by the oral route

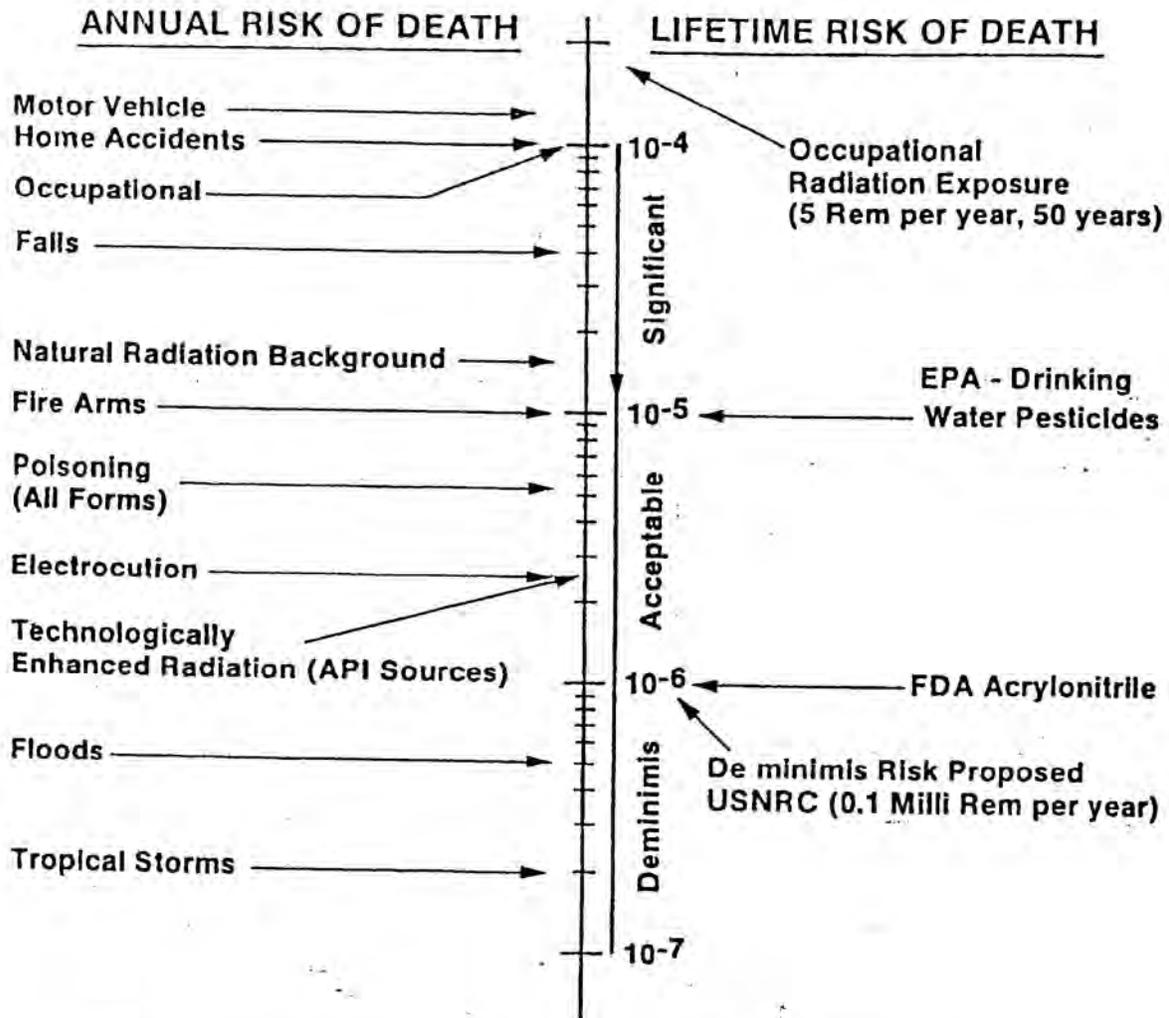
$ALI_{i,j}$ is the annual intake by inhalation which will
provide a risk equal to a deep dose commitment D

$ALI_{o,j}$ is the annual intake by the oral route that will
produce a risk equal to a deep dose commitment D, and

D is the deep dose commitment resulting in an acceptable
level of risk

TABLE 14

DEFINED LEVELS OF RISK



*Being considered in revision of 10CFR 20 Standards for Radiation Protection. This is not an agency position.

The risk factor for whole body radiation is about 1.65×10^{-4} fatal cancers per Rem (ICRP, 1977). If we calculate the committed whole body dose equivalent to produce an excess lifetime risk of 1×10^{-5} , we find

$$10^{-5} \left(\frac{\text{cancer death}}{\text{lifetime}} \right) = D \left(\frac{\text{rem}}{\text{yr}} \right) \times 1.6 \times 10^{-4} \frac{\text{cancer deaths}}{\text{rem}}$$

and that D, the whole body committed dose equivalent whole body, is 62.5 millirem for a single exposure. If we further average that exposure over a lifetime, as would be realistic for an air pollutant, the dose committed is 0.9 millirem/year. It could then be concluded that exposure to radioactive materials in combustion products of interest to the API plus all other sources should be less than 0.9 millirem per year.

The second approach, one based on a variant of derived air concentrations (DAC), is less complicated and perhaps more reasonable. It encompasses a bubble concept in that only that material leaving the plant confines is of interest. If the concentration of radionuclides, Uranium, Thorium, Radon, etc., is less than an established limit based on the Annual Limit of Intake (ICRP, 1980), the plant would be in compliance. It must be recognized that the current occupational DACs would have to be adjusted for 24-hour exposures and for the most susceptible exposed population. Compliance could be judged on an isotope-by-isotope limit or added in the manner of the TLV as below:

$$\frac{\text{Conc U}}{\text{DAC-U}} + \frac{\text{Conc Th}}{\text{DAC Th}} \dots \dots \dots \frac{\text{Conc } ^{210}\text{Pb}}{\text{DAC } ^{210}\text{Pb}} \leq 1$$

where Conc is the concentration of the element of interest and DAC is the derived air concentrations for that environmental exposure.

The advantage of this system would be that each location could measure its own compliance without regard for air modeling, transport and dose response modeling. The disadvantage would be that the measurement is both difficult and expensive to make.

Table 15 compares the two methods and gives estimates of some limits. For either approach, 10^{-5} excess risk permits very small increases over the natural background.

Similar approaches as those suggested to regulate air pollutants are being applied to the development of the Reportable Quantity under CERCLA. Table 16 estimates the amount of raw material or product that will contain one reportable quantity of selected radionuclide for a weight, activity, or dose-equivalent approach. Depending on the mode of definition, very small quantities of petroleum products could easily contain reportable quantities of radionuclides.

Table 15
 Estimate of Radioactive Material Concentrations to Produce
 10^{-5} Lifetime Excess Risk of Fatal Cancer to a Maximum-Exposed Individual

Radioisotope	Solubility Class	Concentrations to Produce 10^{-5} Excess Risk in Target Population (curies per cubic meter)		
		At Stack Generic*	At Fenceline	
			DAC**	MPC**
Uranium 238	D } W } Y }	2.6×10^{-8}	8×10^{-14}	6×10^{-15} (S)
			4×10^{-14}	1×10^{-14} (I)
			2.6×10^{-14}	
Thorium 232	W } Y }	6.5×10^{-11}	6.5×10^{-17}	2×10^{-15} (S)
			1.3×10^{-16}	2×10^{-15} (I)
Radium 226		3.9×10^{-8}	3.9×10^{-14}	(S) 6×10^{-15} (I) 4×10^{-15}
Radon 222		5.2×10^{-6}	5.2×10^{-12}	6×10^{-12}
Lead 210		1.3×10^{-8}	1.3×10^{-14}	8×10^{-15} 1.6×10^{-14}

* Assumes 10^{-6} dilution factor, and the children (10-year old) as the target population, 15 m^3 air inhaled per day (ICRP, 1975).

** Assumes children (10-year) as target population.

TABLE 16

**Amount of Product Needed to
Assemble One Reportable
Quantity of Uranium or Radon**

<u>Item/Product</u>	<u>Possible Form of Reportable Quantity</u>			
	<u>One Pound</u>	<u>One Milli Curie</u>	<u>One Micro Curie</u>	<u>5 Rem Committed Dose Equivalent</u>
Crude Oil	2,162 Bbl	14,200 Bbl	14.2 Bbl	0.5 Bbl
Natural Gas	4.9×10^{16} MCF	714 MCF	714,000 CF	.017 MCF
LPG	4.9×10^{16} MCF	714 MCF	714,000 CF	.071 MCF
US Coal	33.6 T	222 T	0.2 T	.88 T
SRC Product	252 T	1,600 T	1.6 T	.067 T
Shale Oil	890 Bbl	5,882 Bbl	5.8 Bbl	0.24 Bbl
Shale Waste	151 T	1,000 T	1 T	.04 T
Phosphate Rock	3.98 T	26.3 T	.026 T	.001 T
Ground Water	4.4×10^{16} Gals.	6.04×10^8 Gals.	6.04×10^5 Gals.	2.5×10^4 Gals.

Control Options

Any control methodology proposed for radioactive materials must recognize the fact that radioactivity can not be modified or made inert by chemical means. It also must recognize that radioactivity dissipates at fixed rates through fixed sequences or series. Decay to daughter products cannot be guaranteed to reduce the hazard.

The control of emissions of naturally occurring radioactive materials can be accomplished by removing the radioactivity from the raw material or product, or by removing the radioactive materials after combustion. This removal can be accomplished by taking advantage of radioactive decay; by physically removing the radioactive material by washing, filtering, or by absorption; by chemically scrubbing the material from the product or combustion gas stream; or by combination thereof.

The removal of Radon 222 from natural gas could be accomplished by either decay or by absorption on a molecular sieve such as activated charcoal. Radon has a 3.83 day half-life. Storing natural gas for 5 half-lives approximately 20 days would change some 99.5% of the Radon in the influent stream to 21-year Lead 210, much of which will plate out in the storage tanks, pipeline, and process equipment. When one compares the derived air concentration for each, however, it appears that the relative health hazard may have been increased. The DAC for Radon plus daughters, target organ the lung, is 3×10^{-8} Ci per cubic meter, while that for Lead 210, target organ bone, is 1×10^{-10} (ICRP, 1980). Capturing the Radon on a molecular sieve and the Radon daughters on a high-efficiency (HEPA) filter cleans the product stream but changes a very dilute source of radioactive materials into a very concentrated source of radioactivity, presenting both an internal and external radiation hazard.

The removal of Radon from groundwaters can be accomplished by aeration (which releases the radioactive material to the ambient air) or through decay. The decay again introduces Lead 210 into the water which, again, is not totally free of hazard. The Lead 210 can be removed using bacterial filters; i.e., diatomaceous earth, with the resultant hazards associated with concentrating radioactive materials.

Uranium in crude oil presents a somewhat different dilemma. We estimated earlier in this paper that significant quantities of uranium potentially enter our refineries via crude oil. Little is known of its fate, however. Since the law of conservation of matter must apply, it can only end up in the product, the process waste, remain in the process equipment, or escape into the environment. The chemical properties of uranium suggest something concerning its ultimate fate. Uranium can be isolated by reducing uranium halides with alkali or alkaline earth metals or by reducing uranium oxides by calcium, aluminum or carbon at high temperatures. Strong acids can dissolve the metal, but it is relatively unaffected by alkali (CRC, 1981). It would seem likely to find most of the uranium plated out in the process equipment or concentrated in process wastes. Better understanding of the presence and fate of uranium in fuel oils is needed before a control scheme can be proposed.

The main contaminants in coal are members of the Uranium 238 decay series, primarily Radium, Radon, and Uranium. Cleaning the coal will remove much of the radioactive materials on the surface of the coal but will concentrate the material in the waste water. Pulverizing the coal will release much trapped radon to the atmosphere. Combustion will cause most of the radioactivity to be concentrated in the fly ash. High-efficiency scrubbers or filters may be required to reduce the health risks of such exposures to acceptable levels.

Impact of Regulation on API Members

The impact that the regulation of "radionuclides" under the Clean Air Act (CAA) will depend largely upon what the EPA decides is an "acceptable risk". The EPA has been forced to make this decision, and we will know the answer in 180 days.

What the EPA decides depends largely upon what society, as represented by its most vocal members, wants. Table 14 gives some indication of what we might expect, and it is likely that lifetime excess risks greater than one one-hundredth of that imposed by the natural background (1.5×10^{-5}) will be considered unacceptable. It is also equally likely that excess risks less than 10^{-7} will be considered *de minimis*. Table 17 summarizes candidates for regulation for different levels of acceptable risk.

Table 17
Operations Subject to Regulation as a
Function of Defined Acceptable Risk

Acceptable Risk Level (Lifetime Excess Risk of Contracting Fatal Cancer)		
1.5×10^{-5}	5×10^{-6}	1×10^{-6}
Geothermal Power	Groundwater Use (all locations) Geothermal Power	Groundwater Use (all locations) Geothermal Power
Coke Production (all locations)	Coke Production (Northeast only)	Coke Production (all locations)
Coal-Fired Steam	Coal-Fired Steam	Coal-Fired Steam
Coal-Fired Industrial Boilers	Coal-Fired Industrial Boilers	Coal-Fired Industrial Boilers
Underground Coal Mining	Underground Coal Mining Strip Mining (coal)	Underground Coal Mining Strip Mining (coal) Coal Cleaning Natural Gas Combustion Natural Gas Turbines

The impact of CERCLA on API members depends on the definition of reportable quantity. The data collected in this report appear to suggest that the CERCLA will place reporting requirements on many operating locations.

The impact of both regulatory actions is summarized on Table 18. It appears that regulation of radionuclides could impose a severe burden on API member companies and that both regulatory actions should be closely followed.

TABLE 18

Potential Impact of Regulation on API

Operation	Radio-Isotopes	Form	Potential For Regulation		Potential Impact
			CAA	CERCLA	
Production LPG/NG Gas Liquids Crude Oil Water Flood Brine Disposal	$^{222}\text{Rn}+\text{d}$	Gas	X		Removal of Radon (20 day storage)
	$^{222}\text{Rn}+\text{d}$	Liquid	X	X	Removal of Radon (20 day storage)
	$^{235}\text{U}+\text{d}$	Liquid	X	X	Reporting and Control
	$^{222}\text{Rn}+\text{d}$	Gas	X	X	Control Release of Radon
	$^{224}\text{Ra}+\text{d}$	Solid	X	X	Control Release of Radon
Disposal of Scrap Equip., Pipe etc.	$^{235}\text{U}+\text{d}$	Solid		X	Reporting and Control
	^{226}Ra	Solid		X	Reporting and Control
	$^{222}\text{Rn}+\text{d}$	Gas	X	X	of Disposal Site
	^{210}pb	Solid		X	Control of Release of Radon.
Manufacturing Process Heat	$^{222}\text{Rn}+\text{d}$	Gas	X		Control of Release of Radon
Power Generation Gas Turbine Gas Furnace Coal	$^{222}\text{Rn}+\text{d}$	Gas	X		Control of Release of Radon
	$^{222}\text{Rn}+\text{d}$	Gas	X		Control of Release of Radon
	$^{222}\text{Rn}+\text{d}$	Gas	X	X	Control of Release of Radon
	$^{235}\text{U}+\text{d}$	Solid	X	X	Control of Release of Radioactive materials. Control of Release of Radon
	$^{224}\text{Ra}+\text{d}$	Solid and Gas	X	X	Radon from Flyash Disposal Site.
Geothermal Disposal of Process Equip. Bottoms/Sludge	$^{222}\text{Rn}+\text{d}$	Gas	X		Control of Release of Radon
	$^{235}\text{U}+\text{d}$	Solid		X	Reporting and Control of Disposal
	$^{235}\text{U}+\text{d}$	Liquid	X	X	Control of Release of Radon Reporting and Control of Disposal Reporting and Control of Disposal Control of Release of Radon
Coal Mining Underground Strip Mining Cleaning	^{235}U	Solid	X		Control of Release of Radioactive
	$^{224}\text{Ra}+\text{d}$	Solid & Gas	X		Materials and Radon
	ditto	ditto	X		ditto
	ditto	ditto	X	X	Reporting and Control of Waste Disposal Site

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