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

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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 portioning 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 soil*[a]

Rock Type	Potassium-40		Rubidium-87		Thorium-232		Uranium-238	
	percent total Potassium	pCi/g	ppm total Rubidum	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]	0.3–1.1	2–9	10–50	0.2–1	1.6, 2.7	0.2, 0.3	0.5, 0.8	0.2, 0.3
Salic[d]	4–5	30–40	170–200	4–5	16, 20	1.7, 2.2	3.9, 4.7	1.2, 1.6
Granite (Crustal average)	>4	>30	170–200	4–5	17	1.9	3	1
Sedimentary Rocks								
Shale	2.7	22	120[e]	3	12	1.3	3.7	1
Sandstones:								
clean quartz	<1	<8	<40[e]	<1	<2	<0.2	<1	<0.3
dirty quartz	2?	16?	90?	3?	3–6?	0.3–0.7?	2–3?	1?
arkose	2–3	16–24	80–120[e]	2	2?	0.3?	1–2?	0.3–0.7?
Beach sands (unconsolidated)	<1	<8?	<40?	<1?	6	0.7	2	1
Carbonate Rocks	0.3	2	10[e]	0.3	2	0.2	2	0.7
Soils[f]	1.5	12	85[e]	1.4	9	1	1.5	0.6

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

[b] To obtain series equilibrium alpha, beta, or approximate gamma (excluding bremsstrahlung and x radiation) activity, multiply by 6, 4, or 3 respectively.

[c] To obtain series equilibrium alpha, beta, or approximate gamma (excluding bremsstrahlung and x radiation) activity, multiply by 8, 6, 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 ratio with respect to potassium.

[f] In-situ gamma-spectral measurements at 200 locations by Lowder *et al.* (1964).

Table 2 (UNSCEAR, 1977) shows additional data.

TABLE 2. TYPICAL ACTIVITY CONCENTRATION OF ^{40}K, ^{238}U AND ^{232}Th 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

Sources: 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 pCig^{-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}) Average	Range	Reference
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			
Slochteron	...	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	5-1 450	
Texas Panhandle	...	10-520	
Colorado	25.4	11-45	
Project Gasbuggy area	15.8	...	171
California	...	1-100	
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 Average	Range	Reference
Colorado New Mexico	25	0.2-160	1
Texas, Kansas, Oklahoma	<100	5-1450	2
Taxas 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	^{228}Ra	^{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				175
Coal ash (laboratory processing)								
Australia			4.7-8.3					23
Germany, Fed. Rep. of			6.2[c]			2.6		172
	19		5.8				3.4	307a
Japan								
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 ^{214}Bi.
[b] Assumed equal to activity concentration of ^{208}Tl.
[c] Including activity concentration of ^{228}Ra.

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
Coal		
Sample #1	1.3	4.74
Sample #2	1.4	4.24
SRC		
Sample #1	0.8	4.99
Sample #2	1.3	3.73
Coal Particulates		
Sample #1	2.6	14.99
Sample #2	1.9	20.50
SRC Particulates		
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[d] (10^6 t)		Activity concentration (pCi g^{-1})		
	Amount	P_2O_5 content	^{226}Ra	^{238}U	^{232}Th
Marketable rock	38	–	42	41	0.4
Wet process products					
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
Electric furnace process products					
Slag	–	–	56[c]	–	–

Source: Reference 109.

[d] Florida accounts for 82 per cent of the marketable rock production of the United States.

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

[c] The ^{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. Approximaately 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)

Tracts Included	Average Concentration of Radon (pCi/ℓ)
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						
		^{40}K	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{222}Rn	Total
Crude Oil*	uCi/BBL	1.4	0.07		0.17	.04		1.46
Kuwait Oil	uCi/BBL				0.17			0.17
Natural Gas**	uCi/10^6ft^3						1400	1400
LPG	uCi/10^6ft^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 occuring.

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 Gausian 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 11. Summary of radiological impact caused by atmospheric emissions of natural radioactive materials

Source category	Number of sources	Model facility: Principal radionuclide emissions (Ci/y)[a]		Exposure levels: Maximum individual (WL)	Exposure levels: Regional population (Person-WL)	Principal dose equivalent rates:	Maximum individual (mrem/y)[b]	Regional population (Person-rem/y)[c]	Lifetime risk to the maximum individual (x 10^{-6})	Expected fatal cancers per year of operation: Regional population	Expected fatal cancers per year of operation: U.S. (Fatal cancers)
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	0.005	0.5	Lung	350	3.4	10,000	0.01	0.03
		U-238+d	0.4			Bone	360	3.9			
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	0.00005	0.08	Lung	54	17	500	0.004	
		U-238+d	0.03			Bone	79	18			
Phosphoric acid plant	35	Rn-222	480	0.0007	2.0	Lung	85	46	2,000	0.05	
		U-238+d	0.1			Bone	110	45			
Elemental phosphorus plant	9	Rn-222	490	0.0004	2.0	Lung	740	770	6,000	0.1	
		U-238+d	0.15			Bone	570	440			
		Po-210	7.4			Kidney	1800	1400			
Coal-fired power stations[d] (4.4)											
New stations	145	Rn-222	1.9	<0.00001	<0.00001-0.024	Lung	0.8-2.1	0.5-2600	10-60	0.00008-0.2	
		U-238+d	0.3			Bone	1.6-16	1.5-1300			
		Th-232+d	0.07								
Existing stations	250	Rn-222	0.7	<0.00001	<0.00001-0.013	Lung	6.7-15	2.7-19,000	60-700	0.0004-1.5	
		U-238+d	0.8			Bone	8.3-62	7.1-11,000			
		Th-232+d	0.3								

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	Model facility: Principal radionuclide emissions (Ci/y)[a]	Exposure levels: Maximum individual (WL)	Exposure levels: Regional Population (Person-WL)	Principal dose equivalent rates: Maximum Individual (mrem/y)[b]	Principal dose equivalent rates: Regional Population (Person-rem/y)[c]	Lifetime risk to the maximum individual (x 10^{-6})	Expected fatal cancers per year of operation: Population Regional	Expected fatal cancers per year of operation: Population U.S. (Fatal cancers)
Metal mining and milling[e] (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[f] (4.5)	4,200	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

[a]U-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.)
Th-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.
[b]The maximum dose equivalent rate an individual is likely to receive living near the facility.
[c]The 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.
[d]Ranges of impact values represent variations due to station siting.
[e]Includes iron, copper, zinc, and bauxite.
[f]Includes clay, limestone, fluorspar.

Table 12

SUMMARY OF RISKS FROM SOURCES OF AIRBORNE EMISSIONS OF RADIONUCLIDES

Source Category	Principal Radionuclide Emissions (Ci/yr)		Dose Equivalent Rates: Maximum Exposed Individual (mrem/yr)		Dose Equivalent Rates: Collective (person-rem/yr)	Radon Daughter Exposure: Maximum Individual (working level)	Radon Daughter Exposure: Regional Population (person working level)	Health Effects: Lifetime Risk to the Maximum Exposed Individual	Health Effects: Expected Fatal Cancers per Year of Operation to the Population at Risk
Ground Water Treatment Plant (3.1)									
Southeastern Site	Rn-222	8.1	Lung Bone	5.7E-3 1.9E-4	2.9E-2 9.3E-4	3.8E-6	1.9E-2	6E-6	5E-4
Southwestern Site	Rn-222	8.1	Lung Bone	9.6E-3 3.1E-4	0.15 4.9E-3	6.4E-6	0.10	1E-5	2E-3
Geothermal Power Plant (3.2)	Rn-222	5.5E+2	Lung	1.22	3.1	8.1E-4	2.1	1E-3	5E-2
Phosphate (3.3)									
Phosphate Mine: Stack	Rn-222 U-238	2.1E+1 1.8E-2	Lung Bone	3.5E+1 5.8E+1	8.8E+1 2.4E+2	9.7E-6	5.0E-2	1E-4	7E-3
Area Source	Rn-222 U-238	2.6E+3 4.0E-3	Lung Bone	1.7 5.5	9.2 0.3	5.9E-4	3.2	1E-3	2E-2
Phosphate Acid Plant: Stack	Rn-222 Ra-226 U-238	6.5E+1 1.8E-2 3.5E-2	Lung Bone	6.4E+1 1.0E+2	1.5E+2 3.5E+2	3.1E-5	0.16	2E-4	1E-2
Area Source	Rn-222	3.2E+2	Lung	0.22	1.1	1.4E-4	0.75	3E-4	2E-2
Elemental Phosphorus Plant: Stack	U-238 Ra-226 Pb-210 Po-210	2.2E-2 7.0E-3 3.3E-2 3.2E+0	Lung Liver Bone	2.1E+2 1.7E+1 7.0E+1	5.0E+2 2.6E+2 2.5E+2			7E-4	4E-2
Area Source	Rn-222	2.2E+2	Lung	0.15	0.78	1.0E-4	4.3E-2	2E-4	4E-2
Non-Uranium Metal Mining, Milling, Processing (3.4)									
Underground Mine, Area Source #1	Rn-222 U-Nat	2.1E+2 2.3E-5	Lung Bone	0.52 0.21	3.0E-2 7.2E-3	2.7E-4	1.8E-2	4E-4	4E-4
Area Source #2	Rn-222 U-Nat	2.3E+2 1.0E-2	Lung Bone	4.1E+1 6.7E+1	1.2 2.8	2.3E-4	2.0E-2	5E-4	5E-4
Open-Pit Mine	Rn-222 U-Nat	4.5E+3 5.0E-2	Lung Bone	3.6E+1 5.7E+1	2.6 6.5	7.2E-4	0.15	1E-3	4E-3
Copper Ore Mill	Rn-222 U-Nat	1.7E+3 2.0E-2	Lung Bone	7.3E+1 1.2E+2	6.5 1.6E+1	1.6E-3	0.38	3E-3	1E-2

Table 12 (Cont.)

SUMMARY OF RISKS FROM SOURCES OF AIRBORNE EMISSIONS OF RADIONUCLIDES

Source Category	Principal Radionuclide Emissions (Ci/yr)		Dose Equivalent Rates: Maximum Exposed Individual (mrem/yr)		Dose Equivalent Rates: Collective (person-rem/yr)	Radon Daughter Exposure: Maximum Individual (working level)	Radon Daughter Exposure: Regional Population (person working level)	Health Effects: Lifetime Risk to the Maximum Exposed Individual	Health Effects: Expected Fatal Cancers per Year of Operation to the Population at Risk
Non-Uranium Mining, Milling, Processing (Cont)									
Metal Smelter: Main Stack	Rn-222	8.0	Lung	5.3E+1	1.5E+1	Negligible		2E-4	2E-3
	Pb-210	1.0E+1	Liver	1.6E+1	2.4E+1				
	Po-210	1.0E+1	Bone	3.7E+1	4.0E+1				
	U-Nat	4.5E-2							
Area Source	Rn-222	1.7E+2	Lung	2.0E+2	6.3	1.5E-4	1.4E-2	9E-4	6E-4
	U-Nat	5.3E-2	Red Marrow	2.3E+1	1.1				
			Bone	3.2E+2	1.5E+1				
Non-Metal Mining (3.5) Kiln	Rn-222	4.3E-1	Lung	2.0E+1	1.1E+2	Negligible		7E-5	8E-3
	U-Nat	2.8E-4	Liver	1.8	8.3E+1				
			Bone	2.6	1.2E+2				
Area Source	Rn-222	4.3E-1	Lung	0.79	1.3	1.4E-6	6.3E-3	4E-6	2E-4
	U-Nat	5.1E-6	Bone	4.6E-2	1.2				
Coal Mining and Cleaning (3.6) Underground Mine	Rn-222	1.6E+1	Lung	2.6E-2	2.2	Negligible		9E-3	6E-4
	U-238	3.4E-6	Red Marrow	1.6E-2	2.2				
	Th-232	3.5E-6	Bone	3.1E-2	3.3				
Strip Mine	Rn-222	1.4E+0	Lung	1.1	2.3E+1	8.0E-7	3.1E-2	5E-6	2E-3
	U-238	3.6E-4	Bone	2.8	6.4E+1				
	Th-232	2.8E-4							
Coal Cleaning Plant	Rn-222	0.17	Lung	0.27	8.9	Negligible		1E-6	1E-3
	U-238	2.2E-4	Bone	0.69	3.0E+1				
	Th-232	2.2E-4							
Natural Gas Combustion Units (3.7) Natural Gas Boiler	Rn-222	2.4	Lung	2.9E-1	4.5E-2	1.9E-7	3.0E-2	3E-6	6E-4
Natural Gas Turbine	Rn-222	6.7E-2	Lung	5.2E-1	1.3E-2	3.5E-6	8.8E-2	4E-6	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: Maximum Exposed Individual (mrem/yr)		Dose Equivalent Rates: Collective (person-rem/yr)	Radon Daughter Exposure: Maximum Individual (working level)	Radon Daughter Exposure: Regional Population (person working level)	Health Effects: Lifetime Risk to the Maximum Exposed Individual	Health Effects: Expected Fatal Cancers per Year of Operation to the Population at Risk
Coke Production (3.8)									
Northeastern Site	Rn-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	Rn-222	1.9E+0	Lung	1.9E+1	3.6E+1	Negligible		1E-6	3E-3
	Th-232	1.1E-3	Liver	7.1	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 CFSEGS: Midwestern Site	U-238	2.0E-2	Bone	4.2	2.9E+2			5E-5	3E-3
	U-235	1.2E-3							
	Th-232	7.3E-3							
Southeastern Site	U-238	2.0E-2	Bone	1.3E+1	2.2E+1			5E-5	2E-4
	U-235	1.2E-3							
	Th-232	7.3E-3							
Existing CFSEGS: Midwestern Site	U-238	2.9E-2	Bone	1.2+1	7.4E+2			9E-5	1E-2
	U-235	1.6E-3							
	Th-232	2.1E-2							
Southeastern Site	U-238	2.9E-2	Bone	3.1E+1	4.9E+1			5E-5	5E-4
	U-235	2.1E-2							
	Th-232	2.1E-2							
Coal-Fired Industrial Boilers (3.10)									
Eastern Site	U-238	4.5E-3	Lung	7.4	2.3E+2			3E-5	2E-2
	U-235	2.6E-4	Bone	1.8E+1	6.2E+2				
	Th-232	3.3E-3							
Midwestern Site	U-238	4.5E-3	Lung	8.0	1.5E+1			3E-5	1E-3
	U-235	2.6E-4	Bone	2.2E+1	5.2E+1				
	Th-232	3.3E-3							

TABLE 13

Summary of Operations Whose Regulation Will Impact On API Member Companies

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

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 (Teknekron, 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

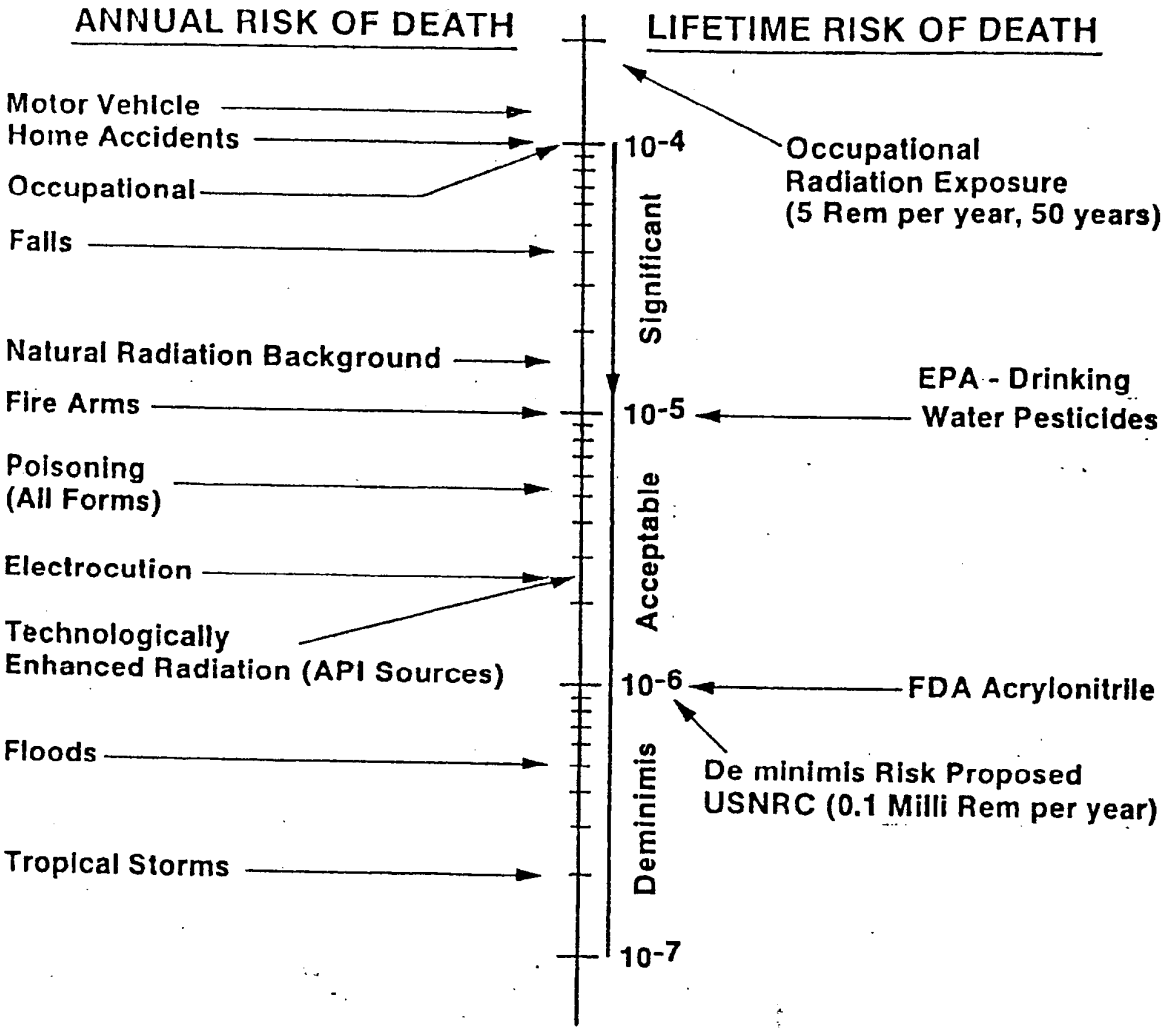
$ALI_{i,j}$ is the annual intake by inhalation which will provide a risk equal to a deep dose commmitment D

$ALI_{o,j}$ 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:

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

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	At Fenceline	
		Generic*	DAC**	MPC**
Uranium 238	D	2.6×10^{-8}	8×10^{-14}	6×10^{-15} (S)
	W		4×10^{-14}	1×10^{-14} (I)
	Y		2.6×10^{-14}	
Thorium 232	W	6.5×10^{-11}	6.5×10^{-17}	2×10^{-15} (S)
	Y		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

Item/Product	Possible Form of Reportable Quantity			
	One Pound	One Milli Curie	One Micro Curie	5 Rem Committed Dose Equivalent
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	1.6T	.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^{9} 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 conversation 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 CAA	Potential For Regulation CERCLA	Potential Impact
Production					
LPG/NG	$^{222}Rn+d$	Gas	X		Removal of Radon (20 day storage)
Gas Liquids	$^{222}Rn+d$	Liquid	X	X	Removal of Radon (20 day storage)
Crude Oil	$^{238}U+d$	Liquid		X	Reporting and Control
Water Flood	$^{222}Rn+d$	Gas	X		Control Release of Radon
Brine Disposal	$^{226}Ra+d$	Solid	X	X	Control Release of Radon Reporting and Control, Disposal Site
Disposal of Scrap Equip., Pipe etc.	$^{238}U+d$	Solid		X	Reporting and Control
	^{226}Ra	Solid		X	of Disposal Site
	$^{222}Rn+d$	Gas	X	X	Control of Release of
	^{210}Pb	Solid		X	Radon
Manufacturing					
Process Heat	$^{222}Rn+d$	Gas	X	X	Control of Release of Radon
Power Generation					
Gas Turbine	$^{222}Rn+d$	Gas	X		Control of Release of Radon
Gas Furnace	$^{222}Rn+d$	Gas	X		Control of Release of Radon
Coal	$^{238}U+d$	Solid	X	X	Control of Release of Radioactive
	$^{226}Ra+d$	Solid	X	X	materials. Control of Release of Radon
		and Gas	X		Radon from Flyash Disposal Site.
Geothermal	$^{222}Rn+d$	Gas	X		Control of Release of Radon
Disposal of Process Equip.	$^{238}U+d$	Solid		X	Reporting and Control of Disposal Control of Release of Radon
Bottoms/Sludge	$^{238}U+d$	Liquid	X	X	Reporting and Control of Disposal Control of Release of Radon
Coal Mining					
Underground	^{238}U	Solid	X		Control of Release of Radioactive
	$^{226}Ra+d$	Solid & Gas	X		Materials and Radon
Strip Mining	ditto	ditto	X		ditto
Cleaning	ditto	ditto	X	X	Reporting and Control of Waste Disposal Site

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