8 December 1978, Volume 202, Number 4372 SCIENCE

Radiological Impact of Airborne Effluents of Coal and Nuclear Plants

Radiation doses from airborne effluents of a coal-fired plant may be greater than those from a nuclear plant.

J. P. McBride, R. E. Moore, J. P. Witherspoon, R. E. Blanco

Summary. Radiation doses from airborne effluents of model coal-fired and nuclear power plants (1000 megawatts electric) are compared. Assuming a 1 percent ash release to the atmosphere (Environmental Protection Agency regulation) and 1 part per million of uranium and 2 parts per million of thorium in the coal (approximately the U.S. average), population doses from the coal plant are typically higher than those from pressurized-water or boiling-water reactors that meet government regulations. Higher radionuclide contents and ash releases are common and would result in increased doses from the coal plant. The study does not assess the impact of nonradiological pollutants or the total radiological impacts of a coal versus a nuclear economy.

Studies have been made in the past few years of the amounts of radioactive substances emitted in the airborne effluents of coal-fired (*1*–*8*) and nuclear (*3*, *6*) power plants. The potential radiological impact of these substances has generally been evaluated in terms of the radiation protection guides set forth by the Federal Radiation Council, the International Commission on Radiological Protection, and the *Code of Federal Regulations* (*9*). The studies showed that releases of radioactive materials from coal-fired and nuclear plants were well within the limits contained in these regulations. Recently, new regulations have been issued that contain numerical design guides for limiting the release of radioactive materials from light-water reactor (LWR) nuclear power plants to values that are "as low as is reasonably achievable" (ALARA) (*10*). These values are about 100 times lower than the radiological guides in the previous regulations.

J. P. McBride is a research staff member of the Chemical Technology Division, R. E. Moore and J. P. Witherspoon are research staff members of the Health and Safety Research Division, and R. E. Blanco is the manager of Radioactive Waste Management Research and Development Programs at Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830.

Therefore, we undertook to evaluate the potential radiological impact of airborne releases of radioactive materials from coal-fired plants and to compare them with the radiological impact of airborne releases from nuclear plants that conform to the new regulations. The method we used was (i) to estimate the annual amounts of airborne radioactive materials released from a model advanced 1000-megawatt electric (MWe) coal-fired plant (the source term), (ii) to calculate the radiological doses received by all exposure pathways, and (iii) to compare the estimated doses with the design objective guidelines specified in the *Code of Federal Regulations* for LWR power stations (*10*) and with the estimated radiological doses from the airborne effluents of a model 1000-MWe pressurized-water reactor (PWR) and a model 1000-MWe boiling-water reactor (BWR). Variables considered for the coal-fired plant were the amounts of radioactive materials in various types of coal and coal ashes, efficiency of fly-ash collection, stack height, and modes by which radioactive materials and radiation are transferred to humans (ingestion, inhalation, direct radiation, and so on).

The results of this study should be construed to represent neither a comparison of the radiological impact of a nuclear versus a coal fuel cycle nor a comparison of the relative health risks of the two types of plants. A complete analysis of the entire nuclear fuel cycle would have to include the radiological impact of mining and milling operations, enrichment facilities, fuel fabrication and refabrication plants, fuel reprocessing, and waste management. Other phases of the coal fuel cycle such as mining and the fate of the bottom ash from the boilers and the ash from the precipitators, which contain most of the radioactivity initially present in the coal, would also have to be considered. These ashes are generally flushed with water to ash ponds, where elements may be leached from the ash and enter the aquatic environment. Health effects associated with the airborne releases of nonradioactive material from coal-fired plants (such as particulates, NO_x, and SO_2) would appear to be many times more significant than those associated with the radioactive releases from either coal-fired or nuclear power plants (*5*).

Natural Radioactivity in Coal

Coal contains small quantities of ^{238}U, ^{235}U, ^{232}Th, and their radioactive daughter products in secular equilibrium (*11*). Secular equilibrium is a steady-state condition in which the rate of formation of the radioactive daughter products is just equal to their rate of decay; that is, the activities of radioactive parent and daughter are the same.

Table 1. Range of uranium and thorium concentrations and geometric means (expected values) for coal samples from various regions of the United States* (N is the number of samples).

Region	Coal rank	N	Uranium (ppm)		Thorium (ppm)	
			Range	Geometric mean	Range	Geometric mean
Pennsylvania	Anthracite	53	0.3–25.2	1.2	2.8–14.4	4.7
Appalachia†	Bituminous	331	<0.2–10.5	1.0	2.2–47.8	2.8
Interior‡	Bituminous	143	0.2–43	1.4	<3–79	1.6
Northern Great Plains§	Subbituminous, lignite	93	<0.2–2.9	0.7	<2.0–8.0	2.4
Gulf‖	Lignite	34	0.5–16.7	2.4	<3.0–28.4	3.0
Rocky Mountain¶	Bituminous, subbituminous	134	<0.2–23.8	0.8	<3.0–34.8	2.0
Alaska	Subbituminous	18	0.4–5.2	1.0	<3.0–18	3.1

*From Swanson *et al.* (*15*). Note that the analyses for U and Th were performed on whole coal. The arithmetic average concentrations of Th and U for all coal samples and various ranks of coal for the whole United States are: all coal, N = 799, 4.7 ppm Th, 1.8 ppm U; anthracite, N = 53, 5.4 ppm Th, 1.5 ppm U; bituminous, N = 509, 5.0 ppm Th, 1.9 ppm U; subbituminous, N = 183, 3.3 ppm Th, 1.3 ppm U; and lignite, N = 54, 6.3 ppm Th, 2.5 ppm U. †Pennsylvania, Ohio, Maryland, West Virginia, Virginia, Kentucky, Tennessee, and Alabama. ‡Michigan, Indiana, Iowa, Nebraska, Missouri, Kansas, Oklahoma, and Arkansas. §North Dakota, Montana, and Wyoming. ‖Alabama, Mississippi, and Arkansas. ¶Wyoming, Colorado, Utah, Arizona, and New Mexico.

The uranium and thorium contents of coal from Illinois and western Kentucky sampled in a study of the Thomas A. Allen steam plant (near Memphis, Tennessee) ranged from 1.7 to 3.3 parts per million (ppm) for uranium and 2.4 to 3.0 ppm for thorium as measured by neutron activation (*12*). In Appalachian coals sampled at the Widows Creek plant (near Bridgeport, Alabama), the uranium and thorium contents, estimated from the specific alpha activity in the ashed coal, ranged from 0.4 to 2.5 ppm and 0.3 to 3.6 ppm, respectively (*7*).

The uranium and thorium contents of fly ash collected at the Allen plant were 30 and 26 ppm, respectively, which, assuming a 10 percent ash content in the coal, extrapolates to 3.0 ppm for uranium and 2.6 ppm for thorium in the coal (*13*). Chemical analysis of the fly ash collected at the Kingston plant (near Kingston, Tennessee) showed a uranium concentration of 25 ppm (*14*).

Eisenbud and Petrow (*1*) measured the amounts of ^{226}Ra and ^{228}Ra in fly ash from the combustion of six samples of Appalachian coal and estimated the average uranium and thorium contents of the coal (assuming secular equilibrium) to be 1.1 and 2 ppm, respectively. Similar extrapolations based on the radium content of the fly ash from a variety of coals (*3*, table 1) give average values for the uranium and thorium contents of the coals of 0.7 to 1.9 ppm, respectively.

Analysis of these data indicated that concentrations of 1 ppm for uranium and 2 ppm for thorium would be representative of coal from these sources, principally Appalachian coal. A survey of the uranium and thorium concentrations in 799 coal samples from all regions of the United States is presented in a draft report of the U.S. Geological Survey (*15*). These data, summarized in Table 1, indicate that concentrations of 1 and 2 ppm for uranium and thorium, respectively, are reasonable estimates of the average values for all U.S. coal. However, the data also show that some coals contain concentrations 10 to 40 times higher than these values. On the basis of these data, we have selected concentrations of 1 ppm for uranium and 2 ppm for thorium in the coal to develop a source term for the airborne releases from the model 1000-MWe coal-fired plant used in this study.

Table 2. Estimated annual airborne radioactive materials released from a model 1000-MWe coal-fired power plant (source term).*

Isotope†	Release (Ci/year per radionuclide)
Uranium-238 chain	
^{238}U, ^{234}Th, ^{234m}Pa, ^{234}U, ^{230}Th, ^{226}Ra, ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, ^{210}Pb, ^{210}Bi, ^{210}Po	8×10^{-3}
Uranium-235 chain	
^{235}U, ^{231}Th, ^{231}Pa, ^{227}Ac, ^{227}Th, ^{223}Ra, ^{211}Pb, ^{211}Bi	3.5×10^{-4}
Thorium-232 chain	
^{232}Th, ^{228}Ra, ^{228}Ac, ^{228}Th, ^{224}Ra, ^{212}Pb, ^{212}Bi	5×10^{-3}
Radon	
^{220}Rn	0.4
^{222}Rn	0.8

*Assumptions: (i) the coal contains 1 ppm U and 2 ppm Th, (ii) ash release is 1 percent, (iii) ^{220}Rn is produced from ^{232}Th in the combustion gases at the rate of 1.38×10^{-9} Ci/sec per gram of Th, (iv) the annual release of natural U is 2.32×10^4 g and of ^{232}Th is 4.64×10^4 g, and (v) 15 seconds is required for the gases to travel from the combustion chamber to the top of the stack. †Except for ^{222}Rn, radionuclides with half-lives less than several minutes are omitted.

Source Term for a Model Advanced 1000-MWe Coal-Fired Power Plant

A source term describing the annual amounts of radioactive materials released from a model advanced 1000-MWe coal-fired power plant was developed from operating data given in a recent mass-balance study for trace elements in one of three units at the Allen steam plant (*12*, *16*). This unit had a peak capacity of 290 MWe at a coal consumption rate of 106 tons per hour. The coal was burned in a cyclone-fed boiler, and the ash was distributed between the slag and fly ash at a ratio of about 3 to 2. (This distribution is in contrast to that obtained in more conventional plants that use a blower-fed boiler, where 80 to 90 percent of the ash appears as fly ash.) The use of a high-efficiency electrostatic precipitator limited the amount of fly ash released to the atmosphere to about 1 percent of the total ash in the coal, which conforms to the Environmental Protection Agency (EPA) emission standards. The percentage of ash released by other coal plants throughout the United States is, in general, higher than this, in some cases more than an order of magnitude higher. Thus, the calculated source term represents the radioactive release when advanced technology is used for abatement of particulate emissions.

Assuming an 80 percent capacity factor, the unit consumes 7.43×10^5 tons of coal per year, which is equivalent to 6.74×10^{11} grams per year or 2.32×10^9 g/MWe-year. Uranium and thorium inputs to the unit at concentrations of 1 ppm for the uranium and 2 ppm for the thorium would be 2.32×10^3 and 4.64×10^3 g/MWe-year, respectively. Assuming that all the uranium and thorium are in the ash (bottom ash in the boiler and fly ash), that 1 percent of the total ash in the coal is released to the atmosphere, and that the nonvolatile radionuclides are distributed uniformly in bottom ash and fly ash, the releases to the atmosphere per megawatt electric per year are about 23.2 g of uranium, 46.4 g of thorium, and associated nonvolatile radioactive daughter products. Annual releases from a 1000-MWe station with the same operating parameters would be 2.32×10^4 g of uranium, 4.64×10^4 g of thorium, and associated nonvolatile radioactive daughter products.

A source term based on the release of 1 percent of the fly ash was calculated (Table 2) assuming that the radioactive daughters of ^{238}U, ^{235}U, and ^{232}Th in the fly ash are in secular equilibrium with the parent elements and are released in the

Table 3. Estimated annual airborne releases (source terms) from a model 1000-MWe boiling-water reactor (BWR) and a model 1000-MWe pressurized-water reactor (PWR).*

Radionuclide	BWR (Ci/year)	PWR (Ci/year)
Argon-41	25	25
Krypton-83m	<1	1
Krypton-85m	150	16
Krypton-85	290	470
Krypton-87	200	3
Krypton-88	240	23
Xenon-131m	18	82
Xenon-133m	<1	120
Xenon-133	3,200	12,000
Xenon-135m	740	<1
Xenon-135	1,100	86
Xenon-138	1,400	<1
Iodine-131	0.3	0.025
Iodine-133	1.1	0.023
Carbon-14	9.5	8
Hydrogen-3 (tritium)	43	1,100

*Source terms for the nuclear plants are from (*20*).

same proportion as the parent elements except for the radon isotopes. All of the radon present in the coal is assumed to be released in the airborne effluent. The 1 percent ash release assumed is nearly an order of magnitude less than the average ash release for the industry in 1972 but approximates the present EPA regulation for the release of particulates to the atmosphere.

Source Terms for Model Advanced Nuclear Plants

The regulations limiting the amounts of radiation received by individuals and populations from nuclear facilities are contained in the *Code of Federal Regulations* (*9*). The general standards are 500 millirems per year to the whole body, gonads, and bone marrow; 1500 mrem/year to other organs; and 170 mrem/year to individuals in populations. On 1 December 1979 new standards for the total uranium fuel cycle superseding these and contained in (*17, 18*) will become effective, limiting off-site exposures to the whole body and all organs except the thyroid to 25 mrem/year; the new thyroid exposure limit is 75 mrem/year. The limiting off-site exposures from radioactive materials in the effluents from LWR's are (*10*): (i) for liquid effluents, 3 mrem/year to the total body and 10 mrem/year to any organ; and (ii) for airborne effluents, 5 mrem/year to the total body and 15 mrem/year to any organ from iodine and particulates. The annual whole-body doses from the natural background external radiation level in the United States vary from a minimum of 75 mrem/year to a maximum of 225; the national average is 105 mrem/year (*19*). The estimated average annual internal whole-body dose from natural radioactivity is about 25 mrem/year (*19*).

All LWR's must conform to the *Code of Federal Regulations*, and consequently it is reasonable to compare the releases of radioactive materials from other power-producing units, such as coal-fired plants, with these regulated values. Such a comparison is made in the present analysis. In addition, airborne releases (source terms) from a model 1000-MWe BWR and a model 1000-MWe PWR are used in the comparison (Table 3). The source terms are from a model BWR and PWR as presented in the *Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light-Water-Cooled Reactors* (GESMO) (*20*). In this analysis, the model reactors are placed in the same location as the coal-fired plant so that the meteorology and population distribution are the same for both.

Dose Calculations

The model coal plant and the nuclear power plants were assumed to be located in the Midwest with meteorology characteristic of St. Louis, Missouri (*21*). The surrounding population was assumed to be 3.5 million people out to 88.5 kilometers (55 miles) from the facility, the average population distribution around three midwestern population centers (*22*). The population density in persons per square kilometer assumed for a radial distance of 8 km from the facilities was 37; from 8 to 40 km, 49; and from 40 to 88.5 km, 170 (*22*).

Maximum individual doses and population doses out to 88.5 km were calculated for both nuclear plants and a coal-fired plant with stack heights of 50, 100, 200, and 300 meters. Radioactive materials released at the top of the stack of the model coal-fired plant were assumed to rise because of the buoyancy of the hot stack gases. The effective release height is the sum of the physical height of the stack and the buoyant plume rise as calculated by use of Briggs' equations (*23*). Information concerning the 122-m stack of the Allen steam plant was used in the plume rise calculations. A 20-m fixed height with no plume rise was used for releases from roof vents of the nuclear plants. These heights are characteristic of existing plants.

Atmospheric dispersion of plumes as they are blown downwind from the plants was estimated by using the Gaussian plume equation of Pasquill (*24, 25*) as modified by Gifford (*26*). The AIRDOS-II computer code (*27*) was used for the atmospheric dispersion calculations. Conversion factors used in AIRDOS-II to calculate doses resulting from immersion in air, exposure to contaminated ground surfaces, and intake through inhalation and ingestion were obtained through the use of computer codes (*28, 29*) employing dosimetric criteria of the International Commission on Radiological Protection (ICRP) (*30*). The factors used for radium isotopes were based on recommendations of the ICRP (*31*). Estimates of the intake of radionuclides through terrestrial food chains were made with the TERMOD model and computer code (*32*) incorporated in the AIRDOS-II code.

Tritium (^3H) and ^{14}C released from nuclear plants were given special treatment because the stable forms of these elements constitute significant fractions of the elemental composition of the human body and our food and drink. Tritium was assumed to exchange with water in the atmosphere and come to equilibrium rapidly with water in the environment, and consequently ingestion doses from tritium were calculated from the specific

Table 4. Maximum individual dose commitments from the airborne releases of model 1000-MWe power plants* compared with *Code of Federal Regulations (CFR)* guides (*10*).

Organ	Maximum individual dose commitment (mrem/year)			
	Coal-fired plant†	BWR‡	PWR‡	*CFR* guide
Whole body	1.9	4.6	1.8	5
Bone	18.2	5.9	2.7	15§
Lungs	1.9	4.0	1.2	15§
Thyroid	1.9	36.9‖	3.8	15§
Kidneys	3.4	3.4	1.3	15§
Liver	2.4	3.7	1.3	15§
Spleen	2.7	3.7	1.1	15§

*The maximum individual dose commitments are for a midwestern site and are estimated at the plant boundary at 500 m from the release points. Dose commitments are less at greater distances. The ingestion component of the dose commitment is based on the assumption that all food is grown and consumed at the reference location. †The dose commitments listed are essentially the same for all stack heights from 50 to 300 m including the plume rises resulting from buoyancy of hot stack emissions. A 1 percent ash release was assumed. The coal was assumed to contain 1 ppm U and 2 ppm Th. ‡Source terms for the nuclear plants are from (*20*). The release height was assumed to be 20 m with no plume rise. §Design guides for doses from iodine and particulates. ‖Assumes dairy cow on pasture at site boundary for entire year. The thyroid dose estimated (*20*, p. IV C-115) for the same source term was 11.7 mrem/year. The lower number results from the assumption that the dairy cow is on pasture only a fraction of a year.

activities of tritium in atmospheric moisture (*33*). The ^{14}C was assumed to be released as CO_2 and come to equilibrium rapidly with natural carbon in the environment through mixing with atmospheric CO_2 and plant photosynthesis. Ingestion of food produced in the area is the only significant exposure mode for ^{14}C (*33*).

Estimated doses from inhalation and ingestion are 50-year dose commitments following 1 year of exposure (that is, the dose received over a 50-year period as the result of the intake in 1 year). Deposited radionuclides were assumed to build up for 50 years in estimating doses from surface exposure. Factors that would reduce external doses, such as shielding provided by dwellings and soil and time spent away from the reference location, were not considered. All of an individual's food was assumed to be produced at the reference location; this is referred to as the 100 percent ingestion dose. Dose calculations assuming 0, 10, 30, and 50 percent production of the consumed food at the reference location were made for comparative purposes.

Results and Discussion

Tables 4 and 5 give the maximum-individual and population dose commitments from the estimated releases of radioactive materials from the model 1000-MWe coal-fired and nuclear power plants. The maximum individual dose commitments for both the coal and the nuclear plants are at the 500-m perimeter.

The maximum individual dose commitments at the 500-m boundaries of the coal-fired and nuclear plants meet the regulations in (*10*) with the exception of the bone dose for the coal-fired plant and the thyroid dose for the BWR (Table 4). [An actual nuclear plant would have to conform to these regulations (that is, a maximum of 15 mrem/year for the thyroid dose at the site boundary). A lower thyroid dose would result from reducing the amount of iodine released or using a site with a greater site-boundary distance, more favorable meteorology, or a greater distance to the nearest dairy pasture.] The data also show that the maximum individual dose commitments from the model coal plant are less than those from the BWR (except for the bone dose) but greater than those from the PWR (except for the thyroid dose). The maximum individual doses at the perimeter of the coal plant are similar for stack heights from 50 to 300 m. This is the result of the assumptions (i) that the washout coefficient for small particles is independent of the height of the particles above the ground (that is, all particles at all heights are washed out to the earth in the same time interval for a particular distance from the stack), and (ii) that the washout effect is much greater than the sum of various dry deposition effects at locations close to the plant. Dry deposition does not make a significant percentage contribution to dose until the plume has traveled far beyond the plant boundary.

Population dose commitments from the coal plant are greater than those from either nuclear plant (Table 5) with the exception of the thyroid dose from the BWR. The ratios of the population dose commitments from the coal-fired plant to those from the nuclear plants are higher than the same ratio for the individual doses at the plant boundary (Tables 4 and 5). This results from the rapid decay of the short-lived noble gases as they move out from the nuclear plant boundaries.

Radium-226 and radium-224 are the major contributors to the whole-body and most organ doses from the coal-fired plant. Assuming that the deposited radionuclides could enter the food chain, ingestion is the main exposure pathway for the population dose commitments from this plant (93 to 96 percent for the whole-body and most organ doses, 83 percent for the bone dose, and 62 percent for the lung dose). Additional exposure is mainly from inhalation. Higher release heights decrease the contribution through inhalation but correspondingly increase the contribution through ingestion.

Carbon-14 is the main contributor to the whole-body and most of the organ doses from both nuclear plants. Ingestion is the major exposure pathway. For the BWR, for example, ingestion accounts for 67 percent of the whole-body population dose commitment and immersion accounts for 32 percent. Corresponding values for the PWR are 76 and 19 percent.

The dose commitments listed in Tables 4 and 5 are based on the assumption that an individual's food is produced entirely at his specific location. It is instructive, however, to compare dose commitments where smaller percentages of one's food are produced locally (Table 6). Results of this comparison show that

Table 5. Population dose commitments from the airborne releases of model 1000-MWe power plants (88.5-km radius).*

Organ	Population dose commitment (man-rem/year)					
	Coal-fired plant† stack height (m)				BWR‡	PWR‡
	50	100	200	300		
Whole body	23	21	19	18	13	13
Bone	249	225	192	180	21	20
Lungs	34	29	23	21	8	9
Thyroid	23	21	19	18	37	12
Kidneys	55	50	43	41	8	9
Liver	32	29	26	25	9	10
Spleen	37	34	31	29	8	8

*The population dose commitments are for a midwestern site. The ingestion components of the dose commitment are based on the assumption that all food is grown and consumed at the reference location. †A plume rise due to buoyancy of hot stack emissions was assumed. The dose commitments are for an ash release of 1 percent and coal containing 1 ppm U and 2 ppm Th. ‡Source terms for the nuclear plants are from (*20*). The release height was assumed to be 20 m with no plume rise.

Table 6. Population dose commitments from the airborne releases of model 1000-MWe power plants as a function of food intake.*

Plant type and organ	Population dose commitment (man-rem/year) if percentage of food grown and consumed in area is				
	0	10	30	50	100
Coal-fired plant†					
Whole body	1.2	3.2	7.2	11.1	21
Bone	31	50	89	128	225
Boiling-water reactor‡					
Whole body	4.3	5.2	6.9	8.7	13
Bone	5.7	7.1	10	13	21
Pressurized-water reactor‡					
Whole body	3.1	4.1	6.1	8.1	13
Bone	4.9	6.4	9.4	12.5	20

*Midwestern site, 88.5-km radius. †Population dose commitments are for coal containing 1 ppm U and 2 ppm Th. The releases are from a 100-m stack with a plume rise due to buoyancy of the hot stack emissions. ‡Source terms for the nuclear plants are from (*20*). The release height was assumed to be 20 m with no plume rise.

dose commitments from the coal plant are reduced more than those from the nuclear plants as the percentage of locally grown food is reduced because ingestion accounts for a higher percentage of the dose from the coal plant. When ingestion is omitted as an exposure pathway (0 percent in Table 6) population dose commitments from the coal plant are less than those from the nuclear plants for the whole body but higher than the nuclear plants for bone.

Jaworowski *et al.* (*8*) discount ingestion as an important pathway of exposure from coal-fired plants on the basis of a comparison of the radium contents of bones from past centuries to those of the present day, but find that exposures from inhalation are still greater for coal-fired plants than for nuclear plants. However, they state that the radium in fly ash is more soluble than that in soil and that the radionuclide concentrations (^{226}Ra, Th, and U) in vegetation in areas surrounding coal plants are higher than those in vegetation in agricultural areas, which supports the assumption that ingestion is a significant pathway of radiological exposure from a coal-fired plant.

The public health significance of the estimated dose commitments for the model plants is relatively minor. Using an estimate of 100 to 200 health effects (that is, cancer mortality and genetic effects in the first two generations following exposure) per 10^6 whole-body man-rems (*34*), it is estimated that there could be 0.001 to 0.003 health effect for each year of operation of the model nuclear plant. For the model coal-fired plant, 0.002 to 0.005 health effect is estimated for each year of operation under conditions that give the highest population dose commitment for the assumed coal radionuclide contents and ash release. However, higher dose commitments and enhanced radiation health effects from a coal-fired plant are possible (see below).

Effect of higher uranium and thorium concentrations on dose commitments. The dose commitments given in Tables 4 and 5 were based on the combustion of coal with uranium and thorium contents of 1 and 2 ppm, respectively (the base case). The use of coals with higher uranium and thorium concentrations could result in higher dose commitments. These higher dose commitments, at the same 1 percent ash release assumed in the base case, can be estimated from

$$D_n = C_u f_{un} D_b + (C_t/2) f_{tn} D_b$$

where D_n is the dose commitment to organ n for the new case; D_b is the dose commitment to organ n for the base case; C_u is the uranium concentration for the new case; C_t is the thorium concentration for the new case; f_{un} is the fraction of the dose to organ n contributed by the uranium chains in the base case; and f_{tn} is the fraction of the dose to organ n contributed by the thorium chain in the base case.

Table 7. Factors for estimating the effect of variations in uranium and thorium concentrations in coal on the dose commitments to various organs.

Organ	Maximum individual dose		Population dose	
	f_{un}	f_{tn}	f_{un}	f_{tn}
Whole body	0.78	0.22	0.77	0.23
Bone	0.82	0.18	0.82	0.18
Lungs	0.78	0.22	0.64	0.36
Thyroid	0.78	0.22	0.77	0.23
Kidneys	0.87	0.13	0.90	0.10
Liver	0.82	0.18	0.84	0.16
Spleen	0.84	0.16	0.86	0.14

Table 7 lists the factors (f_{un} and f_{tn}) to be used in calculating the dose commitments to the various organs. The factors were obtained by analyzing the base case and determining the separate contributions of the uranium and thorium chains to the exposures.

Effect of higher fly-ash releases on dose commitments. Releases of fly ash from most of the currently operating coal-fired plants, particularly older plants, are higher than 1 percent. Dose commitments from a coal plant with a fly-ash release greater than 1 percent may be estimated from the doses calculated for a model 1000-MWe plant with a 1 percent ash release by multiplying them by (i) the percentage of ash released to the atmosphere as fly ash and (ii) the electrical capacity of the station (in megawatts) divided by 1000. Appropriate allowances must be made for the stack height in estimating the population dose commitments.

In a recent report by the Federal Power Commission (*35*), which summarizes the releases from 696 major steam plants in 1972, it is estimated that 3,607,000 tons of fly ash were released to the atmosphere in that year as a result of the combustion of 348,694,000 tons of coal with an average ash content of 13.4 percent (by weight). This indicates an average release to the atmosphere of 8 percent of the total ash in the coal burned—eight times the ash release assumed in evaluating the radiological impact of the model coal-fired plant in this article.

Emission regulations for coal-fired steam plants set by the EPA require that the emission not be greater than 0.1 pound of particulates (that is, fly ash) per million British thermal units of fuel (*36*). This number corresponds to a release to the atmosphere of about 1 percent of the total ash in the coal burned, the value used in this article.

Conclusion

The radiological impact of naturally occurring radionuclides emitted in the airborne effluent of a model advanced 1000-MWe coal-fired steam plant, burning coal with a uranium content of 1 ppm and a thorium content of 2 ppm and releasing 1 percent of the total ash in the coal to the atmosphere, was evaluated and compared with the impact of the radioactive materials in the airborne effluents of model 1000-MWe light-water reactors. Computer codes developed at Oak Ridge National Laboratory were used to assess the doses. The major pathway of exposure for the radioactivity in the emissions from both the coal-fired plant and the nuclear plants was ingestion of contaminated foodstuffs. For the nuclear plants, immersion in the airborne effluents was also a significant pathway.

The estimated maximum individual dose commitments outside the plant perimeters for all plants (i) occurred at the assumed plant boundary (500 m from the plant), (ii) were independent of stack height in the case of the coal-fired plant (because of the exposure pathway and the scavenging of particulates by rainfall), and (iii) were, in general, less than the design guides imposed on nuclear plants by the regulations in (*10*).

The maximum individual 50-year dose commitments from the model coal-fired plant were greater than those from the PWR, except for the thyroid dose, but were less than those from the BWR, except for the bone dose. In general, however, whole-body and all organ dose commitments for both the coal-fired and nuclear plants were within the same order of magnitude. The estimated 50-year dose commitments to the whole body per year of plant operation in millirems, were: coal plant, 1.9; BWR, 4.6; and PWR, 1.8. The 50-year dose commitment from the annual airborne releases from both the model coal-fired and nuclear plants should be viewed in the perspective of the annual dose resulting from natural background radioactivity. For the United States the average annual dose from natural radioactivity, external plus internal radiation, is 130 mrem/year.

Whole-body and organ population dose commitments within a radius of 88.5 km ranged in all cases from 50 per-

cent higher to several times higher for the coal-fired plant than for the nuclear plants, except for the thyroid dose from the coal-fired plant. The estimated annual whole-body population dose commitments in man-rems were: coal-fired plant, 21 (100-m stack); BWR, 13; and PWR, 13. For bone dose, the values in man-rems were: coal-fired plant, 225; BWR, 21; and PWR, 20. In making these estimates it was assumed that 100 percent of the consumed food is grown at the reference point for the dose calculation. If the amount of food grown locally is reduced from 100 to 0 percent, the annual population dose commitments for whole-body exposures in man-rems are: coal-fired plant, 1.2; BWR, 4.3; and PWR, 3.1. For bone doses, the values are: coal-fired plant, 31; BWR, 5.7; and PWR, 4.9. It is concluded that the public health significance of these above dose commitments is relatively minor, but higher dose commitments from a coal-fired plant are possible (see below). Health effects associated with airborne releases of nonradioactive material from coal-fired plants (particulates, NO_x, SO_2, and so on) would appear to be many times more significant than those associated with the radioactive releases from either coal-fired or nuclear power plants (*5*).

The assumed release to the atmosphere of 1 percent of the total ash in the coal burned approximates the EPA regulation for the release of particulates to the atmosphere. The average ash release for coal-fired steam plants operating in 1972 was 8 percent, and some older plants have much higher ash releases. Coals having uranium and thorium concentrations higher than the assumed values of 1 and 2 ppm, respectively, are common. The use of such coals and higher ash releases could result in dose commitments from a coal-fired plant more than an order of magnitude higher than those calculated above. Methods for estimating these higher dose commitments have been presented.

References and Notes

1. M. Eisenbud and H. G. Petrow, *Science* **144**, 288 (1964).
2. J. G. Terrill, Jr., E. D. Harward, I. P. Leggett, Jr., *Ind. Med. Surg.* **36**, 412 (1967).
3. J. E. Martin, E. D. Harward, D. T. Oakley, in *Environmental Effects of Producing Electric Power* (Committee Print, Joint Committee on Atomic Energy, 91st Congress, 1st Sess., November 1969), pp. 773–809. See also J. E. Martin, E. D. Harward, D. T. Oakley, J. M. Smith, P. H. Bedrosian, in *Environmental Aspects of Nuclear Power Stations* (SM-146/19, International Atomic Energy Agency, Vienna, 1971), pp. 325–327.
4. A. P. Hull, *Nucl. Saf.* **12** (No. 3), 185 (1971).
5. L. B. Lave and L. C. Freeburg, *ibid.* **14** (No. 5), 409 (1973).
6. A. P. Hull, *Nucl. News* **17** (No. 5), 51 (1974).
7. P. A. Bedrosian, D. G. Easterly, S. L. Cummings, *Radiological Survey Around Power Plants Using Fossil Fuel* (EERL 71-3, Environmental Protection Agency, Montgomery, Ala., 1970).
8. Z. Jaworowski, J. Bilkiewicz, E. Dobosz, D. Grzybowska, L. Kownacka, Z. Wronski, in *Environmental Surveillance Around Nuclear Installations* (SM-180/20, International Atomic Energy Agency, Vienna, 1973), vol. 1, pp. 403–412.
9. *Code of Federal Regulations*, title 10, part 20.
10. *Ibid.*, title 10, part 50, appendix I.
11. N. P. Goldstein, K. H. Sun, J. L. Gonzales, *Trans. Am. Nucl. Soc.* **14**, 66 (1971).
12. N. E. Bolton, R. I. van Hook, W. Fulkerson, W. S. Lyon, A. W. Andren, J. A. Carter, J. F. Emery, *Trace Measurements at the Coal-Fired Allen Steam Plant* (ORNL-NSF-EP-43, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1973).
13. W. Fulkerson *et al.*, *Allen Steam Plant Study* (ORNL-5030, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1975), pp. 77–82.
14. F. G. Seeley, personal communication.
15. V. E. Swanson *et al.*, *U.S. Geol. Surv. Open-File Rep. 76-468* (1976) (draft).
16. D. H. Klein *et al.*, *Environ. Sci. Technol.* **9**, 973 (1975).
17. *Code of Federal Regulations*, title 40, part 190.
18. *Fed. Regist.* **42**, 2858 (1977).
19. A. W. Klement, Jr., C. R. Miller, R. P. Minx, B. Schlein, *Estimates of Ionizing Radiation Doses in the United States 1960–2000* (ORP/CSD 72-1, Environmental Protection Agency, Montgomery, Ala., 1972).
20. *Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light-Water-Cooled Reactors* (NUREG-0002, Nuclear Regulatory Commission, Washington, D.C., 1976), vol. 3, pp. IV C-104 to IV C-106.
21. *Seasonal and Annual Wind Distribution by Pasquill Stability Classes (6) STAR Tabulation* (National Oceanic and Atmospheric Administration, St. Louis, January 1965 to December 1969).
22. B. C. Finney, R. E. Blanco, R. C. Dahlman, G. S. Hill, F. G. Kitts, R. E. Moore, J. P. Witherspoon, *Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle—Reprocessing Light-Water Reactor Fuel* (ORNL/NUREG/TM-6, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1977), pp. 59–87.
23. G. A. Briggs, *USAEC Rep. TID-25075* (1969).
24. F. Pasquill, *Meteorol. Mag.* **90**, 1063 (1961).
25. D. H. Slade, *USAEC Rep. TID-24190* (1968).
26. F. A. Gifford, Jr., *Nucl. Saf.* **2** (No. 4), 47 (1961).
27. R. E. Moore, *The AIRDOS-II Computer Code for Estimating Radiation Dose to Man from Airborne Radionuclides in Areas Surrounding Nuclear Facilities* (ORNL-5245, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1977).
28. W. D. Turner, S. V. Kaye, P. S. Rohwer, *EXREM and INREM Computer Codes for Estimating Radiation Doses to Populations from Construction of a Sea-Level Canal with Nuclear Explosives* (ORGDP Rep. K-1752, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1968).
29. G. G. Killough, P. S. Rohwer, W. D. Turner, *INREM—A FORTRAN Code Which Implements ICRP 2 Models of Internal Radiation Dose to Man* (ORNL-5003, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1975).
30. "Report of Committee 2 on permissible dose for internal radiation," *ICRP Publ. 2* (1959).
31. "Report of Committee 4 on evaluation of radiation doses to body tissues from internal contamination due to occupational exposure," *ICRP Publ. 10* (1968).
32. R. S. Booth and S. V. Kaye, *A Preliminary Systems Analysis Model of Radioactivity Transfer to Man from Deposition in a Terrestrial Environment* (ORNL/TM-3135, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1971).
33. G. G. Killough and L. R. McKay, *A Methodology for Calculating Radiation Doses from Radioactivity Released to the Environment* (ORNL-4992, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1976).
34. Report of the Advisory Committee on the Biological Effects of Ionizing Radiation, *The Effect on Populations of Exposure to Low Levels of Ionizing Radiation* (National Academy of Sciences, Washington, D.C., 1972).
35. *Steam-Electric Plant Air and Water Control Data for the Year Ending December 31, 1972* (FPC-S-246, Federal Power Commission, Washington, D.C., 1975).
36. *Fed. Regist.* **36**, 247 (1971).

37. This article is based on a more detailed report by the same authors: *Radiological Impact of Airborne Effluents of Coal-Fired and Nuclear Power Plants* (ORNL-5315, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1978). Oak Ridge National Laboratory is operated by Union Carbide Corporation under contract W-7405-eng-26 with the Department of Energy.