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Radiological Impact of Airborne Effluents of Coal-Fired and Nuclear Power Plants

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RADIOLOGICAL IMPACT OF AIRBORNE EFFLUENTS OF COAL-FIRED AND NUCLEAR POWER PLANTS

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ABSTRACT

Radiological impact of naturally occurring radionuclides in airborne effluents of a model coal-fired steam plant [1000 MW(e)] is evaluated assuming a release to the atmosphere of 1 percent of the ash in the coal burned and compared with the impact of radioactive materials in the airborne effluents of model light-water reactors [1000 MW(e)]. The principal exposure pathway for radioactive materials released from both types of plants is ingestion of contaminated foodstuffs. For nuclear plants immersion in the airborne effluents is also a significant factor in the dose commitment. Assuming that the coal burned contains 1 ppm uranium and 2 ppm thorium together with their decay products and using the same impact analysis methods used in evaluating nuclear facilities, the maximum individual dose commitments from the coal plant for the whole body and most organs (except the thyroid) are shown to be greater than those from a pressurized-water reactor (PWR) and, with the exception of the bone and kidney doses, less than those from a boiling-water reactor (BWR). With the exception of the bone dose, the maximum individual dose commitments from the coal plant are less than the numerical design guideline limits listed in 10 CFR 50, Appendix I, for light-water reactors (LWRs). Population dose commitments from the coal plant are higher than those from either nuclear plant, except for the thyroid dose from the boiling-water reactor. The use of coal containing higher uranium concentrations and/or higher particulate releases ($\gg 1\%$), characteristic of the present coal-fired power industry, could result in dose commitments from a coal plant several orders of magnitude higher than those estimated in this study. Methods for estimating these higher dose commitments are presented. The study is limited to a comparison of the radiological impacts of airborne effluents from model coal-fired and nuclear power plants and does not compare the total radiological impacts of a coal versus a nuclear economy. It is concluded that an evaluation of the radiological impact on the environment should be included in the assessment of both coal-fired and nuclear power plants.

1. INTRODUCTION

Studies have been made in the past few years of the amounts of naturally occurring radioactive substances emitted in the airborne effluents of coal-fired power plants (1-5) as well as the radioactivity in the releases from nuclear power plants (3, 6). 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 Part 20 of Title 10 of the Code of Federal Regulations. The studies showed that releases of radioactive materials from coal-fired plants and nuclear plants were well within the limits contained in these regulations. However, where estimates were made of the radiological impact of stack effluents of the coal plants, the studies were limited to an assessment of the radiological dose through the inhalation pathway and did not include the ingestion pathway (3, 7). Ingestion is the important pathway when considering radioactive materials such as radium and thorium. Recently, new regulations have been issued which contain numerical design guides for limiting the release of radioactive materials from light-water-reactor (LWR) nuclear power plants to values which are "as low as is reasonably achievable" (ALARA) (8). These values are about 100 times lower than radiological guides in the previous regulations. Therefore, we undertook to reevaluate airborne releases of radioactive materials from coal-fired plants, to estimate the potential radiological impact (doses to individuals and populations) of these releases, and to compare them with the airborne releases and radiological impacts from nuclear plants that conform to the new regulations. The method used was (i) to estimate the annual amounts of airborne radioactive materials released from a model advanced 1000-MW(e) coal-fired plant (the source term), (ii) to calculate the radiological doses received via 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 CFR 50, Appendix I), and with the estimated radiological doses from the airborne effluents of a model 1000-MW(e) pressurized-water reactor (PWR) and a model 1000-MW(e)

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 man (i.e., ingestion, inhalation, direct radiation, etc.).

Results of the present analysis should not be construed to represent a complete comparison of the radiological impact of a nuclear energy economy versus a coal economy. A true comparison would have to include the entire nuclear fuel cycle for a nuclear power economy (i.e., mining and milling operations, enrichment facilities, fuel fabrication and refabrication plants, fuel reprocessing, and waste management), and analysis of the impact of other phases of the coal fuel cycle such as mining and waste management. For example, the fate of the bottom ash from the boilers and precipitators of the coal plant, which contains most of the radioactivity initially present in the coal, would determine the potential for additional radiation exposure from the coal fuel cycle. These ashes are generally flushed with water to ash ponds where elements may be leached from the ash and enter the aquatic environment in runoff. Similarly, the toxic effects of radioactive waste materials produced at coal mines should be evaluated.

The present survey is limited to a comparison of the radiological impacts of the airborne effluents from coal-fired and nuclear power plants. The amounts of radioactive materials released in liquid effluents from nuclear power plants are well known and have been documented (6). However, the rate of movement of radioactive materials from coal slag and ash piles in leaching waters is not known. Consequently, a comparison of the radiological impact of the liquid effluents from coal-fired and nuclear power plants was not made.

2. NATURAL RADIOACTIVITY IN COAL

Coal contains small quantities of ^{238}U, ^{235}U, ^{232}Th, and their radioactive daughter products in secular equilibrium (9). 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, i.e., activities of radioactive parent and daughter are the same.

Uranium and thorium contents of coal from Illinois and Western Kentucky sampled in a study of the Allen plant (near Memphis, Tenn.) ranged from 1.7 to 3.3 ppm uranium and 2.4 to 3.0 ppm thorium as measured by neutron activation (10). 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).

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 and no enrichment of the elements in the fly ash, extrapolates to 3.0 ppm uranium and 2.6 ppm thorium in the coal (11). Chemical analysis of the fly ash collected at the Kingston plant (near Kingston, Tenn.) showed a uranium concentration of 25 ppm (12).

Eisenbud and Petrow 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 (1). Similar extrapolations based on the radium content of the fly ash from a variety of coals in ref. 3 (cf. Table 1) give average values for the uranium and thorium contents of the coals of 0.7 to 1.9 ppm, respectively.

An analysis of the data in Tables 1 and 2 indicate that concentrations of 1 ppm uranium and 2 ppm throium would be representative of coal from these sources, principally Appalachia 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 by the United States Department of the Interior Geologic Survey (13). These data are summarized in Table 3 and indicate that concentrations of 1 ppm for uranium and 2 ppm for thorium in coal are reasonable estimates of the average values for all coal in the United States. However, the data also show that some coals contain concentrations several orders of magnitude higher than these values. Based on these data, we have selected concentrations of 1 ppm uranium and 2 ppm thorium in the coal to develop a source term for the model 1000-MW(e) coal plant used in this study. Comparisons were also made for the combustion of coal containing 2 ppm of uranium and 2 ppm of thorium.

Table 1. Radioactivity in fly ash from coal[a]

Source	Investigator	Concentration (pCi/g dry fly ash)			
		^{226}Ra	^{228}Ra	^{228}Th	^{232}Th
Appalachian coal[b]	Eisenbud et al.	3.8	2.4	2.6	c
Utah coal	Eisenbud et al.	1.3	0.8	1.0	c
Wyoming coal	Eisenbud et al.	c	1.3	1.6	c
Alabama coal	Eisenbud et al.	2.3	2.2	2.3	c
TVA coal	Stone	4.3	2.9	2.9	2.9
Hartsville coal[d]	SERHL[e]	2.3	3.1	c	3.1
Colbert, TVA, coal[f]	SERHL	3.1	6.9	1.6[g]	6.9[g]
Widows Creek, TVA, coal	SERHL	1.6	2.7	2.8	2.7

[a] J. E. Martin, E. D. Harward, and D. T. Oakley, "Comparison of Radioactivity from Fossil-Fuel and Nuclear Power Plants," Environmental Effects of Producing Electric Power - Part I. Appendix 14, Committee Print, Joint Committee on Atomic Energy 91st Congress of the U.S., 1st Session, Table 1, p. 777, Washington, D. C., November 1969.

[b] Average values for samples of fly ash obtained from the combustion of 6 different samples of semibituminous coal from Appalachian mines.

[c] Analysis not performed.

[d] Average values for ^{226}Ra and ^{232}Th in 5 samples of fly ash; ^{228}Ra assumed in secular equilibrium with ^{232}Th.

[e] Southeastern Radiological Health Laboratory, HEW Bureau of Radiological Health; since December 1970, the Eastern Environmental Radiation Laboratory, Environmental Protection Agency, Montgomery, Alabama.

[f] Average of 12 samples; ^{228}Ra assumed in secular equilibrium with ^{232}Th.

[g] One of these numbers would appear to be in error. In secular equilibrium, the activities of ^{228}Th and ^{232}Th should be the same.

Table 2. Uranium and thorium contents of various coals

Coal source	Investigator	Estimation method[a]	Concentration (ppm) Uranium	Thorium
Allen, TVA	Bolton et al.	Neutron activation[b]	2.7	2.7
West Kentucky	Bedrosian et al.	Specific alpha activity: ashed coal	2.1	0.6
East Tennessee	Bedrosian et al.	Specific alpha activity: ashed coal	1.3	0.6
North Alabama	Bedrosian et al.	Specific alpha activity: ashed coal	2.5	1.0
Widows Creek, TVA	Bedrosian et al.	Specific alpha activity: ashed coal	0.5	2.1
Allen, TVA	Fulkerson et al.	Chemical analysis uranium, thorium in fly ash	3.0	2.6
Kingston, TVA	Seeley	Chemical analysis uranium in fly ash	2.5	-
Appalachia	Eisenbud et al.[c]	^{226}Ra, ^{228}Ra in fly ash	1.1	2.0
Utah	Eisenbud et al.[c]	^{226}Ra, ^{228}Ra in fly ash	0.4	0.7
Alabama	Eisenbud et al.[c]	^{226}Ra, ^{228}Ra in fly ash	0.6	1.8
Wyoming	Eisenbud et al.[c]	^{228}Ra in fly ash	-	1.1
TVA	Stone[c]	^{226}Ra, ^{232}Th in fly ash	1.3	2.6
Hartsville	SERHL[c,d]	^{226}Ra, ^{232}Th in fly ash	0.6	2.8
Colbert, TVA	SERHL[c]	^{226}Ra in fly ash	0.8	-
Widows Creek, TVA	SERHL[c]	^{226}Ra, ^{232}Th in fly ash	0.5	2.5
		Range	0.4-3.0	0.6-2.8
		Average	1.4	1.8

[a]Where coal sample was not analyzed directly for uranium and thorium, the uranium and thorium contents were estimated from analyses of the fly ash assuming 10% ash in the original coal and secular equilibrium with the radioactive daughters.

[b]Average values for uranium and thorium contents in 3 and 2 samples of coal, respectively (cf Ref. 9).

[c]Estimated from information in Table 1, Ref. 3, p. 777 (cf Table 1 of this report).

[d]Southeastern Radiological Health Laboratory, HEW Bureau of Radiological Health; since December 1970, the Eastern Environmental Radiation Laboratory, Environmental Protection Agency, Montgomery, Alabama.

Table 3. Range of uranium and thorium concentrations and geometric means (expected values) for coal samples taken from various regions of the United States[a]

Region	Coal rank	Number of samples	Uranium concentration (ppm)		Thorium concentration (ppm)	
			Range	Geometric mean	Range	Geometric mean
Pennsylvania	Anthracite	53	0.3-25.2	1.2	2.8-14.4	4.7
Appalachia[b]	Bituminous	331	<0.2-10.5	1.0	2.2-47.8	2.8
Interior[c]	Bituminous	143	0.2-43	1.4	<3-79	1.6
Northern Great Plains[d]	Subbituminous, lignite	93	<0.2-2.9	0.7	<2.0-8.0	2.4
Gulf[e]	Lignite	34	0.5-16.7	2.4	<3.0-28.4	3.0
Rocky Mountain[f]	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

[a] V. E. Swanson, J. H. Medlin, et al., "Collection, Analysis, and Evaluation of Coal Samples in 1975," U.S. Department of the Interior, Geological Survey, Open-File Report, 76-468 (1976) Draft.

[b] Pennsylvania, Ohio, Maryland, West Virginia, Virginia, Kentucky, Tennessee, Alabama.

[c] Michigan, Indiana, Iowa, Nebraska, Missouri, Kansas, Oklahoma, Arkansas.

[d] North Dakota, Montana, Wyoming.

[e] Alabama, Mississippi, Arkansas.

[f] Wyoming, Colorado, Utah, Arizona, New Mexico.

Note: The analyses for uranium and thorium were performed on whole coal.
The arithmetic average concentrations of thorium and uranium in ppm for all coal samples and various ranks of coal for the whole United States are as follows:

Coal rank	Samples	Thorium (ppm)	Uranium (ppm)
All coal	799	4.7	1.8
Anthracite	53	5.4	1.5
Bituminous	509	5.0	1.9
Subbituminous	183	3.3	1.3
Lignite	54	6.3	2.5

3. SOURCE TERM FOR A MODEL ADVANCED 1000-MW(e) COAL-FIRED POWER PLANT

The source term describing the amounts of radioactive materials released from a model advanced 1000-MW(e) 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 TVA's Thomas A. Allen steam plant at Memphis, Tenn. (10, 14). This unit had a peak capacity of 290 MW(e) at a coal consumption rate of 106 tons/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 EPA emission standards (See Sect. 6.4). The percentage of ash released by other coal plants throughout the United States is, in general, higher than this and, in some cases, more than an order of magnitude higher (See Sect. 6.4). Thus the calculated source term represents the radioactive release when the most advanced available 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} g/year or 2.32×10^9 g/MW(e)-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 g/MW(e)-year and 4.64×10^3 g/MW(e)-year, respectively. Assuming that all the uranium and thorium are in the ash and that 1 percent of the ash in the coal is released to the atmosphere, about 23.2 g/MW(e)-year of uranium and 46.4 g/MW(e)-year of thorium and associated nonvolatile radioactive daughter products would be released with the ash. Annual releases from a 1000-MW(e) station with the same operating parameters would be 2.32×10^4 g of uranium and 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 4) assuming that the radioactive daughters of ^{238}U, ^{235}U and

Table 4. Estimated annual airborne radioactive materials released from a model 1000 MW(e) coal-fired power plant (source term)[a]

Isotope	Releases (Ci/year)
U-238 chain	
U-238	8×10^{-3}
Th-234	8×10^{-3}
Pa-234m	8×10^{-3}
U-234	8×10^{-3}
Th-230	8×10^{-3}
Ra-226	8×10^{-3}
Po-218	8×10^{-3}
Pb-214	8×10^{-3}
Bi-214	8×10^{-3}
Po-214	8×10^{-3}
Pb-210	8×10^{-3}
Bi-210	8×10^{-3}
Po-210	8×10^{-3}
U-235 chain	
U-235	3.5×10^{-4}
Th-231	3.5×10^{-4}
Pa-231	3.5×10^{-4}
Ac-227	3.5×10^{-4}
Th-227	3.5×10^{-4}
Ra-223	3.5×10^{-4}
Rn-219	3.5×10^{-4}
Pb-211	3.5×10^{-4}
Bi-211	3.5×10^{-4}
Tl-207	3.5×10^{-4}
Th-232 chain	
Th-232	5×10^{-3}
Ra-228	5×10^{-3}
Ac-228	5×10^{-3}
Th-228	5×10^{-3}
Ra-224	5×10^{-3}
Pb-212	5×10^{-3}
Bi-212	5×10^{-3}
Tl-208	1.8×10^{-3}
Radon releases	
Rn-220	0.4
Rn-222	0.8

[a]Assumptions: (1) the coal contains 1 ppm uranium and 2 ppm thorium, (2) ash release is 1 percent, (3) Rn-220 is produced from Th-232 in the combustion gases at the rate of 1.38×10^{-9} curies per second per gram of thorium, (4) the annual release of natural uranium is 2.32×10^{4} g and of Th-232 is 4.64×10^{4} g, and (5) 15 sec is required for the gases to travel from the combustion chamber to the top of the stack.

^{232}Th in the fly ash are in secular equilibrium with the parent elements and are released in the same proportion as the parent elements except for the radon isotopes. All of the radon initially 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 (See Sect. 6.4).

4. SOURCE TERMS FOR MODEL ADVANCED NUCLEAR PLANTS

The regulations for limiting the release of radioactive materials from light-water reactors (LWRs) to unrestricted areas are contained in the Code of Federal Regulations, Title 10, Parts 50 and 20 (10 CFR 50 and 10 CFR 20). Regulations for licensing of production and utilization facilities are contained in 10 CFR 50, and the numerical guides for design objectives and limiting conditions for the operation of LWRs are contained in Appendix I of 10 CFR 50. The guides for all types of nuclear facilities for limiting the amounts of radiation received by individuals and populations are contained in 10 CFR 20. The general standards are 500 millirem/year to the whole body, gonads, and bone marrow; 1500 millirem/year for other organs; and 170 millirem/year for individuals in populations. On Dec. 1, 1979, new standards for nuclear power operations superseding 10 CFR 20 and contained in 40 CFR 190 will become effective limiting exposures to the whole body and all organs except the thyroid to 25 millirem/year; the new thyroid exposure limit is 75 millirem/year (15). In addition, 10 CFR 20 requires that all nuclear facilities must hold the releases to "as low as is reasonably achievable, taking into account the state of technology, the economics of improvements in relation to benefits to the public health and safety, other societal and socioeconomic considerations, and in relation to the utilization of atomic energy in the public interest." The design guides for limiting the amounts of radioactive materials in the effluents from LWR reactors in 10 CFR 50, Appendix I, are the following: (i) for liquid effluents, 3 millirem/year for whole body and 10 millirem/year for organs, and (ii) for airborne effluents, 5 millirem/year for whole body and 15

millirem/year from iodine and particulates for organs. Supplementary treatment equipment for retaining radioactive materials must be added to a plant if the cost is less than about $1000/whole-body-man-rem or about $1000/thyroid-man-rem over a distance of 80.5 km (50 miles) from the plant. The whole body doses from natural background radiation levels in the United States vary from a minimum of 100 millirem/year to a maximum of 245; the national average is 130 (16).

All LWRs 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 or oil-fired plants, with these regulatory values. Such a comparison is made in the present analysis. In addition, airborne releases (source terms) from a model 1000-MW(e) pressurized-water reactor (PWR) and a model 1000-MW(e) boiling-water reactor (BWR) are also used in the comparison (Table 5). The source terms are from uranium-oxide-fueled LWRs - a model BWR and a model PWR with recirculating U-tube-type steam generators - given in the Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light-Water-Cooled Reactors (GESMO, ref. 17). The radwaste systems for each type of plant contain equipment and features typical of current operating plants; however, the plants are models, and the source terms are not directly applicable to a particular operating reactor. 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 the two types of plants. The maximum individual doses and the population doses for the nuclear plants are evaluated at the boundary of the plant restricted area (assumed to be 500 m) and in the unrestricted area from the plant boundary out to 88.5 km (55 miles), respectively. The maximum doses in the unrestricted area occur at the plant boundary and doses decrease with distance out from the boundary.

5. DOSE CALCULATIONS

Both the model coal plant and the nuclear power plants were assumed to be located in the midwest with meteorology characteristic of St. Louis, Missouri (18). The surrounding population was assumed to be 3.5 million

Table 5. Estimated annual airborne releases (source terms) from a model 1000-MW(e) boiling-water reactor (BWR) and a model 1000-MW(e) pressurized-water reactor (PWR)[a]

Radionuclide	BWR (Ci/year)	PWR (Ci/year)
^{41}Ar	25	25
^{83m}Kr	b	1
^{85m}Kr	150	16
^{85}Kr	290	470
^{87}Kr	200	3
^{88}Kr	240	23
^{131m}Xe	18	82
^{133m}Xe	b	120
^{133}Xe	3,200	12,000
^{135m}Xe	740	b
^{135}Xe	1,100	86
^{138}Xe	1,400	b
^{131}I	0.3	0.025
^{133}I	1.1	0.023
^{14}C	9.5	8
^{3}H	43	1,100

[a]Source terms for the nuclear plants are from the Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, U.S. Nuclear Regulatory Commission, NUREG-0002 (April 1976), Vol. 3, Chap. IV, pp. IV C-104 and IV C-106.

[b]Annual release < 1 Ci.

people out to 88.5 km from the facility, the average population distribution around three midwestern population centers (19). 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 (19). Maximum individual doses and population doses out to 88.5 kilometers were calculated for both nuclear plants and for stack heights of 50, 100, 200, and 300 m for the coal plant. Radioactive materials released at the top of the stack of the model coal 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 through the use of Brigg's equations (20). Information from the 122-m Allen steam plant stack 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 using the Gaussian plume equation of Pasquill (21, 22) as modified by Gifford (23). Radionuclides released as particulates deposit on ground surfaces through the processes of dry deposition and scavenging. The rate of dry deposition, which involves adsorption, particle interception, diffusion, and chemical-electrostatic effects, was estimated by multiplying the concentration of the radionuclide in air at ground level by the deposition velocity. A value of 1.0 cm/sec was used for the deposition velocity of all particulates. Particle sizes were assumed to be small enough that gravitational settling could be ignored. The rate of deposition by scavenging, which is primarily the process of washout by rainfall, was estimated by multiplying together three factors: (i) the average concentration of the radionuclide in air above the reference location from the ground to the bottom of the inversion layer, (ii) the distance from the ground to the bottom of the inversion layer, and (iii) the scavenging coefficient. A scavenging coefficient of 2×10^{-5} sec^{-1} was used for all particulates. Methods for estimating the scavenging coefficient, which is related to the rainfall rate (ca. 89 cm/year at the midwestern site) can be found in ref. 21. The value used represents an average over the year, i.e., scavenging was calculated as though it were

occurring continuously. Depletion of the plume by deposition processes and radioactive decay as it is blown downwind was taken into account in the calculations.

The AIRDOS computer code (24) was used for the atmospheric dispersion calculations, using annual-average meteorological data in terms of joint frequencies of wind-speed categories, atmospheric stabilities, and wind direction. The computer code estimates annual-average concentrations in air at ground level and ground deposition rates for each radionuclide released from the plants for each of 16 compass directions as a function of distance from the source. Each concentration and deposition rate is an average value across a 22.5° sector. Concentrations in air for each sector and distance from the source are used in AIRDOS to calculate dose via inhalation and immersion in air. Ground surface concentrations are used for the estimation of external radiation esposure. The ground deposits are also assimilated into food, which results in additional doses through ingestion.

Dose conversion factors used in AIRDOS 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 (25, 26) that use dosimetric criteria of the International Commission on Radiological Protection (ICRP) and other recognized authorities. Most of the dose conversion factors were based on dosimetric criteria given in ICRP-2 (27), but those factors used for radium isotopes were based on recommendations in ICRP-10 (28).

Estimates of the intake of radionuclides by man through terrestrial food chains were made with a model and computer code (29), incorporated within the AIRDOS code, which treats ingestion of vegetable crops, beef, and milk.

Tritium (^{3}H) and ^{14}C released from nuclear plants are given special treatment because the stable forms of these elements constitute significant fractions of the elemental composition of the human body and man's food and drink. Transport processes within soil, plants, cattle, and man which apply to trace quantities of radionuclides do not necessarily apply to these cases where the stable elements are present in such quantities that saturation effects are significant. Tritium was assumed to exchange with

water in the atmosphere and to follow water precisely through the environment. Ingestion doses from tritium were calculated from the specific activities of tritium in atmospheric moisture (30). The ^{14}C was assumed to be released in the form of CO_2 and become available for plant photosynthesis after mixing with atmospheric CO_2. Ingestion of food produced in the area is the only significant exposure mode for ^{14}C, so the dose estimates were based on the specific activity of ^{14}C in atmospheric CO_2 (30).

With the exception of ^{3}H and ^{14}C, mentioned above, estimates of intake by man of radioactivity from nuclear and coal sources were determined with the TERMOD code. The TERMOD model and computer code are described in refs. 29 and 30. The latter reference contains all of the radionuclide-dependent and independent input variables used in the analysis. In this model, airborne radioactive materials are deposited upon crop plants, soil, and pasture grass. All radionuclides are assumed to be soluble, both in terms of uptake by vegetation and absorption after ingestion by cattle and man. Losses of radioactivity due to weathering (14-day half-life on crops and pasture), radiological decay, and food preparation (crops) are assumed. Vegetation is contaminated externally (fallout) and via uptake from roots. Radionuclides deposited on pastures are transferred to cattle and then to man via ingestion of beef and milk. Daily intakes assumed for maximally exposed individuals were 250 g of vegetables, 300 g of beef, and 1 liter of milk. The daily intake for exposed populations differed in that a value of 0.3 liter per day of milk was used.

Deposited radionuclides are assumed to build up for a period of 50 years for the purpose of estimating doses from surface exposure. Relatively short-lived radionuclides reach a steady-state concentration on the surface long before 50 years. Only gamma radiation is considered for estimating surface exposure. Annual surface dose estimates are conservatively high because (i) they are based on the assumption that a man stands on the ground surface at his place of residence during the entire year, and (ii) no consideration is given to the long-term penetration of radionuclides into the soil with consequent shielding by the soil layer.

Dose estimates via inhalation and ingestion are 50-year dose commitments accrued from 1 year of exposure to facility releases. Factors that

would tend to reduce external doses, such as shielding provided by dwellings and time spent away from the reference location, are not considered. Moreover, in estimating dose to individuals through ingestion of plants, meat, and milk, an individual is assumed to obtain all of his food at the reference location, referred to as 100-percent ingestion dose. Dose calculations assuming 0-, 10-, 30- and 50-percent ingestion were also made for comparative purposes.

5.1 Source Term Methodology

Radionuclides released as particulates from the coal plant are members of three radionuclide decay chains starting with ^{238}U, ^{235}U, and ^{232}Th. The first five daughters of the ^{238}U chain (^{234}Th, ^{234m}Pa, ^{234}U, ^{230}Th, and ^{226}Ra) were assumed to be in equilibrium at the time they left the stack. Equilibrium treatment was discontinued after ^{226}Ra because it decays to ^{222}Rn. All of the ^{222}Rn present in the coal burned is assumed to be released to the atmosphere; this amount is considerably greater than the amount of ^{222}Rn produced by the decay of the ^{226}Ra released to the atmosphere (Table 4). Surface decay of each of the short-lived nuclides in the source term following ^{222}Rn (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) was calculated to proceed in accordance with its own decay constant. The daughters of ^{210}Pb (^{210}Bi and ^{210}Po) were assumed to be in equilibrium with ^{210}Pb.

The first six daughters of ^{235}U (^{231}Th, ^{231}Pa, ^{227}Ac, ^{227}Th, ^{223}Ra, and ^{219}Rn) were considered to be in equilibrium with ^{235}U in the plume and on ground surfaces. Each of the short-lived nuclides following the noble gas ^{219}Rn (^{211}Pb, ^{211}Bi, and ^{207}Tl) was calculated to decay in accordance with its own decay constant.

Equilibrium treatment of the thorium chain (^{232}Th, ^{228}Ra, ^{228}Ac, ^{228}Th, and ^{224}Ra) was halted with ^{224}Ra because it decays to ^{220}Rn. All of the ^{220}Rn in the coal burned enters the plant exhaust system, and the amount released to the atmosphere is very much greater than that produced by the decay of the ^{224}Ra released to the atmosphere (Table 4). Radionuclides in the original source term following ^{220}Rn (^{212}Pb, ^{212}Bi, and ^{208}Tl) were considered to decay in accordance with the decay constant of

^{212}Pb. The decay of ^{220}Rn in the original source term is nearly complete by the time the plume reaches the plant boundary. To approximate this situation, a quantity of its daughter product, ^{212}Pb, was added to the source term, which corresponds to the release rate of ^{220}Rn multiplied by the ratio of the half-lives of ^{220}Rn and ^{212}Pb. The dose conversion factor for surface exposure used for this specific release of ^{212}Pb included contributions from its daughters ^{212}Bi and ^{208}Tl.

Radioactive daughter-products as solid particulates are produced in the effluent plume from the nuclear plants as a result of decay of some of the short-lived noble gases released. The buildup of particulate daughters in the plume was treated conservatively by adding them to the source term itself. Decay of ^{88}Kr ($T_{1/2}$ = 2.8 hour) produces the shorter-lived ^{88}Rb ($T_{1/2}$ = 17.8 min). Even though equilibrium with its parent is not achieved by the time the plume reaches the 500-m plant boundary, a release of ^{88}Rb equivalent to that of its parent was used. Decay of ^{88}Rb in the plume was assumed to take place at the same rate as that of its parent, ^{88}Kr. The decay of ^{88}Rb after deposition on the ground was calculated to occur in accordance with its own radioactive decay constant. The noble gas ^{138}Xe decays in the plume to produce a longer-lived particulate daughter, ^{138}Cs, which was added to the source term with a release rate reduced from that of its parent by the daughter-to-parent ratio of the radioactive decay constants. The release rate of ^{138}Cs was 54.3 percent of that of its parent, ^{138}Xe.

6. RESULTS AND DISCUSSION

Tables 6 and 7 give the maximum individual dose commitments and the population dose commitments calculated to result from the estimated releases of radioactive materials from the model 1000-MW(e) coal-fired and nuclear power plants. As noted in Sect. 3.0, the source term for the coal plant assumes a concentration of 1 ppm uranium and 2 ppm thorium in the coal and a release of 1 percent of the fly ash. The maximum individual doses for both the coal and the nuclear plants are the maximum values at a 500-m perimeter.

Table 6. Maximum individual dose commitments from the airborne releases of model 1000-MW(e) power plants (mrem/year)[a]

Organ	Coal-fired plant[b]	Boiling-water reactor[c] (BWR)	Pressurized-water reactor[c] (PWR)	10 CFR 50 Appendix I guides
Whole body	1.9	4.6	1.8	5
Bone	18.2	5.9	2.7	15[e]
Lungs	1.9	4.0	1.2	15[e]
Thyroid	1.9	36.9[d]	3.8	15[e]
Kidneys	3.4	3.4	1.3	15[e]
Liver	2.4	3.7	1.3	15[e]
Spleen	2.7	3.7	1.1	15[e]

[a]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 locations.

[b]The dose commitments listed are essentially the same for all stack heights from 50 to 300 m including the plume rises resulting from bouyancy of hot stack emissions. A 1 percent ash release was assumed. The coal was assumed to contain 1 ppm uranium and 2 ppm thorium.

[c]Source terms for the nuclear plants are from the Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, U.S. Nuclear Regulatory Commission, NUREG-0002 (April 1976), Vol. 3, Chap. IV, pp. IV C-104, and IV C-106. The release height was assumed to be 20 m with no plume rise.

[d]Assumes dairy cow on pasture at site boundary for entire year. The thyroid dose estimated in GESMO (ref. 17, p. IV C-115) for the same source term was 11.7 mrem/year.

[e]Design guides for doses from iodine and particulates.

Table 7. Population dose commitments from the airborne releases of model 1000-MW(e) power plants (man-rem/year; 88.5-km radius)[a]

Organ	Coal-fired plant[b] stack height (m)				Boiling-water reactor[c] (BWR)	Pressurized-water reactor[c] (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

[a]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 locations.

[b]A plume rise due to buoyancy of hot stack emissions was assumed. The dose commitments are for an ash release of 1 percent and for coal containing 1 ppm uranium and 2 ppm thorium.

[c]Source terms for the nuclear plants are from the Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, U.S. Nuclear Regulatory Commission, NUREG-0002 (April 1976) Vol. 3, Chap. IV, pp. IV C-104, and IV C-106. The release height was assumed to be 20 m with no plume rise.

The maximum individual doses at the 500-m boundary of the coal plant meet the Appendix I regulations with the exception of the bone dose (Table 6). The maximum individual doses for the nuclear plants also meet the Appendix I regulations, with the exception of the thyroid dose from the BWR. An actual nuclear plant would have to conform to the Appendix I regulations (i.e., a maximum of 15 millirem/year for the thyroid dose at the site boundary). A lower dose would result from reducing the amount of iodine released, a site-location with a greater site-boundary distance, more favorable meteorology, or a greater distance to the nearest dairy pasture. The data of Table 6 also show that the maximum individual dose commitments from the model coal plant are less than those from a BWR (except for the bone dose) but are greater than the doses from the PWR (except for the thyroid dose). The maximum individual doses at the perimeter of the coal plant are essentially the same for all 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 (i.e., all particles at all heights are washed out to the earth in the same time interval for a given distance from the stack); and (ii) that the washout effect is much greater than the sum of various dry deposition effects at distances close to the plant. Dry deposition does not make a significant percentage contribution to dose until the plume has travelled far beyond the plant boundary.

Population dose commitments from the coal plant are greater than those from either nuclear plant (Table 7) with the exception of the thyroid dose from the BWR. The ratio of the population doses for the coal plant to the nuclear plants is higher than the same ratio for the individual doses at the plant boundary (Tables 6 and 7). This results from the rapid decay of the short-lived noble gases released from the nuclear plants as they move from the plant boundaries out to 88.5 km.

6.1 Percentage Contributions of Radionuclides to Exposure and Exposure Pathways

Table 8 lists the percentage contributions of radionuclides to the population doses from the coal-fired plant. The radium nuclides, ^{226}Ra and ^{228}Ra, are the major contributors to the whole-body dose and most

Table 8. Percentage contributions of radionuclides to population doses from the airborne releases of a 1000-MW(e) coal-fired power plant[a]

Organ	Contributions of radionuclides (percent)[b]							
	^{226}Ra	^{228}Ra	^{228}Th	^{230}Th	^{232}Th	^{210}Po	^{210}Pb	^{227}Ac
Whole body	67	21	0.7	3.5	0.7	2.5	2.1	1.0
Bone	59	14	1.8	12	1.8	0.9	4.9	2.6
Lungs	47	15	10	10	10	2.1	1.7	0.7
Thyroid	68	21	0.7	3.5	0.7	2.5	2.1	1.0
Kidneys	28	8.4	0.6	11	0.6	29	18	0.9
Liver	48	15	0.2	4.2	0.2	16	11	4.7
Spleen	42	13	0.4	2.2	0.4	40	1.2	0.6

[a]Percentage contributions are for coal containing 1 ppm uranium and 2 ppm thorium. The radionuclides are assumed to be released from a 50-m stack at a midwestern site with a plume rise due to buoyancy of the hot stack emissions.

[b]The horizontal columns total less than 100 percent because radionuclides contributing only to a minor extent to the organ doses are not listed. Release heights greater than 50 m result in slightly higher contributions from the radium nuclides and lower contributions from ^{230}Th.

organ doses. However, ^{210}Po is the major contributor to spleen dose, and ^{210}Po and ^{210}Pb together contribute almost half of the dose to the kidneys. The contribution of ^{222}Rn to the doses is insignificant even though its release rate is much greater than that of any other nuclide in the source term. The lung is the critical organ for ^{222}Rn, but the ^{222}Rn contribution to the total lung dose is only about 1 part in a million.

Ingestion is the main exposure pathway for the population doses from the coal-fired plant (Table 9). The results listed in Tables 8 and 9 apply to a release height of 50 m. Higher release heights decrease the contribution via inhalation with a corresponding increase in the percentage contribution via ingestion. For whole body and most organs, about 27 percent of the ingestion dose is caused by consumption of vegetables, about 29 percent from milk, and about 44 percent from beef. Between 40 and 55 percent of the ingestion dose to kidneys, liver, and spleen comes from consumption of vegetables with correspondingly lower contributions via the milk and beef pathways.

Percentage contributions of radionuclides to the population doses from the nuclear power plants are listed in Tables 10 and 11. Carbon-14 is the main contributor to whole body and most of the organ doses for both nuclear plants. Tritium also adds significantly to the PWR doses. The gases from the nuclear plants are released at a height of 20 m. The maximum dose occurs at the plant boundary (500 m), and the dose decreases with increasing distance from the plant.

Ingestion is the major exposure pathway for both types of nuclear plants, but immersion in the airborne releases is also important (Tables 12 and 13). For the BWR, for example, ingestion accounts for 67 percent of the whole-body population dose and immersion accounts for 32 percent. Corresponding percentages for the PWR are 76 and 19 percent. Beef is the major food source for the ingestion doses to whole-body and all organs except thyroid. Milk is the major source of thyroid dose.

Even though the airborne effluent from the coal-fired plant is released from tall stacks (50-300 m) rather than at the 20-m height used for the nuclear plants, the maximum doses for the coal-fired plant also occur close to the plant and doses decrease with increasing distance. This is

Table 9. Percentage contributions of exposure pathways to population doses from the airborne releases of a 1000-MW(e) coal-fired power plant[a]

Organ	Contribution by pathway (percent)[b]		
	Inhalation	Surface exposure	Ingestion
Whole body	5.5	0.9	93.6
Bone	17.0	0.1	82.9
Lungs	37.2	0.4	62.4
Thyroid	5.6	0.8	93.6
Kidneys	14.4	0.2	85.4
Liver	6.5	0.4	93.1
Spleen	3.6	0.3	96.1

[a]Percentage contributions are for coal containing 1 ppm uranium and 2 ppm thorium. The radionuclides are assumed to be released from a 50-m stack at a midwestern site with a plume rise due to buoyancy of the hot stack emissions.

[b]Release heights greater than 50 m result in decreasing the percentage contribution through inhalation and increasing the percentage contribution through ingestion.

Table 10. Percentage contributions of radionuclides to population doses from the airborne releases of a model 1000-MW(e) boiling-water reactor[a]

Organ	Percent contributions of radionuclides[b]						
	^{14}C	^{135m}Xe	^{135}Xe	^{133}Xe	$^{88}Kr + {}^{88}Rb$	^{131}I	^{133}I
Whole body	65.4	10.4	6.6	4.7	6.0	0.5	0.2
Bone	71.7	8.0	6.2	5.2	4.0	0.4	0.1
Lungs	46.7	16.1	9.8	6.2	9.7	0.9	0.3
Thyroid	10.6	3.9	2.3	2.0	2.0	67.8	9.5

[a]Source terms for the BWR are from the Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, U.S. Nuclear Regulatory Commission, NUREG-0002 (April 1976), Vol. 3, Chap. IV, p. IV C-104.

[b]Percentage contributions are for a release of radionuclides at a midwestern site at a height of 20 m with no plume rise. Minor contributors to organ doses are not listed in this table.

Table 11. Percentage contributions of radionuclides to population doses from the airborne releases of a model 1000-MW(e) pressurized-water reactor[a]

Organ	Contributions of radionuclides (percent)[b]			
	^{14}C	^{3}H	^{133}Xe	^{131}I
Whole body	54.6	26.2	17.7	0.04
Bone	61.8	17.1	19.9	0.03
Lungs	36.3	39.9	21.6	0.07
Thyroid	27.8	29.1	23.2	17.7

[a]Source terms for the PWR are from the Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, U.S. Nuclear Regulatory Commission, NUREG-0002 (April 1976), Vol. 3, Chap. IV, p. IV C-106.

[b]Percentage contributions are for a release of radionuclides at a midwestern site at a height of 20 m with no plume rise. Minor contributors to organ doses are not listed in this table.

Table 12. Percentage contributions of exposure pathways to population doses from the airborne releases of a model 1000-MW(e) boiling-water reactor[a]

	Contribution by pathway (percent)[b]			
Organ	Inhalation	Immersion	Surface exposure	Ingestion
Whole body	0.3	31.6	1.5	66.6
Bone	0.2	26.3	1.1	72.5
Lungs	2.0	46.9	2.4	48.7
Thyroid	1.7	11.4	0.5	86.4

[a]Source terms for the BWR are from the Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, U.S. Nuclear Regulatory Commission, NUREG-0002 (April 1976), Vol. 3, Chap. IV, p. IV C-104.

[b]Percentage contributions are for a release of radionuclides at a midwestern site at a height of 20 m with no plume rise.

Table 13. Percentage contributions of exposure pathways to population doses from the airborne releases of a model 1000-MW(e) pressurized-water reactor[a]

	Contribution by pathway (percent)[b]			
Organ	Inhalation	Immersion	Surface exposure	Ingestion
Whole body	4.6	19.1	0.04	76.3
Bone	3.0	21.1	0.03	75.9
Lungs	8.1	22.6	0.05	69.2
Thyroid	5.4	24.7	0.04	69.8

[a]Source terms for the PWR are from the Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, U.S. Nuclear Regulatory Commission, NUREG-0002 (April 1976), Vol. 3, Chap. IV, p. IV C-106.

[b]Percentage contributions are for a release of radionuclides at a midwestern site at a height of 20 m with no plume rise.

because ingestion is the major pathway of exposure for nearly all of the radionuclides released by the coal plant and results primarily from the deposition of radionuclide particulates through washout of elevated plumes by rainfall. The maximum concentration of radionuclides in air at ground level, which determines the maximum dose through immersion in air and inhalation, occurs at a distance of several kilometers from a plant with a tall stack; however, the surface deposition rate per unit area through washout, which largely determines ingestion and surface doses, is high close to the stack and decreases with increasing distance.

This paper analyzes the impact of hypothetical operating plants. However, the long-term effects of the radioactive materials released should also be noted. In general, the long-lived materials released from coal-fired plants (such as uranium, thorium, and radium) represent a localized long-term effect. The releases from the nuclear plants are primarily gases which are readily lost from the surrounding area. The localized effect of long-lived materials such as ^{14}C and tritium is transitory since they eventually become widely dispersed through physical and biological processes.

It is recognized that the models used to describe the movement of radioactive materials through the environment to man after their release are based on limited data. It would be desirable to obtain more definitive information on the relationship between the actual amounts of radioactive materials released and the actual radiation exposures incurred by the populations surrounding the plants.

6.2 The Effect of Varying Food Intakes on Dose Commitments

The dose commitments listed in Tables 6 and 7 are based on the assumption that each person's food is produced entirely at his specific location (Sect. 5). Most people, however, consume food produced at a variety of locations - often at great distances from their area of residence. It is, therefore, instructive to compare dose commitments resulting from the plant releases of radionuclides for various percentages of food intake from the local area. Results of this comparison show that dose commitments from the coal plant are reduced more than those from the

nuclear plants as the percentage of food intake from the local area is reduced because ingestion accounts for a higher percentage of the dose from the coal plant than from the nuclear plants (Tables 9, 12, and 13). When ingestion is omitted as an exposure pathway (0 percent in Table 14), however, population dose commitments from the coal plant are less than those from the nuclear plants for whole body but are significantly higher for bone.

The assumptions of 100-percent solubility for the radionuclides in the TERMOD ingestion dose calculations and 100 percent of the diet grown locally and 50-year accumulation of radionuclides for surface radiation dose calculations (See Sect. 5) produce conservatively high dose estimates. However, the same assumptions and techniques were used in evaluating the releases from both the coal and nuclear plants and are commonly used in evaluating the impacts from all types of nuclear facilities. On the other hand, the optimistic assumption of low or zero solubility for the radioactive material released from the coal plant (i.e., zero ingestion) still gives significant population dose commitments when compared to the doses from the releases from nuclear plants (Table 14).

6.3 Effect of Higher Uranium and Thorium Concentrations on Dose Commitments

The dose commitments given in Tables 6 and 7 were based on the combustion of coal containing 1 ppm uranium and 2 ppm thorium (i.e., the base case). The uranium and thorium contents of some coals are much higher than these values as illustrated by the data in Table 3; use of such coals could result in higher dose commitments. These dose commitments at the same 1-percent ash release assumed in the base case can be estimated using the following equation:

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

where

D_n = the dose commitment to organ n for the new case;

D_b = the dose commitment to organ n for the base case;

C_u = the uranium concentration (ppm) for the new case;

Table 14. Population dose commitments from the airborne releases of model 1000-MW(e) power plants as a function of food intake (man-rem/year)[a]

	Percent of food grown and consumed in area				
	0	10	30	50	100
Coal-fired plant[b]					
Whole body	1.2	3.2	7.2	11.1	21
Bone	31	50	89	128	225
Boiling-water reactor (BWR)[c]					
Whole body	4.3	5.2	6.9	8.7	13
Bone	5.7	7.1	10	13	21
Pressurized-water reactor (PWR)[c]					
Whole body	3.1	4.1	6.1	8.1	13
Bone	4.9	6.4	9.4	12.5	20

[a]Midwestern site, 88.5-km radius.

[b]Population dose commitments are for coal containing 1 ppm uranium and 2 ppm thorium. The releases are from a 100-m stack with a plume rise due to buoyancy of the hot stack emissions.

[c]Source terms for the nuclear plants are from the Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, U.S. Nuclear Regulatory Commission, NUREG-0002, (April 1976), Vol. 3, Chap. IV, pp. IV C-104, and IV C-106. The release height was assumed to be 20 m with no plume rise.

C_t = the thorium concentration (ppm) for the new case;

f_{un} = the fraction of the dose to organ n contributed by the uranium chains in the base case;

f_{tn} = the fraction of the dose to organ n contributed by the thorium chain in the base case.

Table 15 lists the factors (f) to be used in calculating the dose commitments to the various organs.

As an illustration, Table 16 shows the dose commitments from a model 1000-MW(e) coal plant with a 1-percent ash release using coal containing 2 ppm of uranium and 2 ppm of thorium.

6.4 The Effect of Higher Fly-Ash Releases on Dose Commitments

The 1-percent ash release assumed for the coal plant is optimistically low. Releases of fly ash from most of the currently operating coal plants are higher than 1 percent. Releases from older plants, in particular, are generally much higher. Dose commitments resulting from a coal plant with a fly-ash release greater than 1 percent may be easily estimated by multiplying the doses calculated for a model 1000-MW(e) plant with a 1-percent ash release (i) first by the percent of ash released to the atmosphere as fly ash by the coal plant, and (ii) second, by a number derived by dividing the electrical capacity of the station in megawatts 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 (31) which summarizes the releases from 696 major steam plants in the year 1972, it is estimated that 3,607,000 tons of fly ash were released to the atmosphere in that year as the result of the combustion of 348,694,000 tons of coal with an average ash content of 13.4 percent (by weight). This would extrapolate to an average release to the atmosphere of 8 percent of the total ash in the coal burned and 8 times the ash release assumed in evaluating the radiological impact of the model coal plant in this paper. The FPC report is the latest in a continuing series of reports on power plant statistics (the first covered the year 1969) and includes

Table 15. Factors for estimating the effect of variations in uranium and thorium concentrations in coal on the dose commitments to various organs

Organ	Maximum individual doses		Population doses	
	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 16. Radiological dose commitments from a model 1000-MW(e) coal-fired steam plant using coal containing 2 ppm of uranium and 2 ppm of thorium[a]

Organ	Maximum individual[b] (mrem/yr)	Population[c] (man-rem/yr) Stack height (m) 50	100	200	300
Whole body	3.4	40	38	33	32
Bone	33	454	410	351	328
Lungs	3.4	56	48	39	36
Thyroid	3.4	40	37	33	32
Kidneys	6.4	105	96	82	77
Liver	4.4	59	54	48	45
Spleen	5.0	68	64	57	54

[a]The dose commitments are for a midwestern site. The ingestion component is based on the assumption that all food is grown and consumed at the reference locations. A 1% ash release is assumed.

[b]The maximum individual dose commitments are approximately the same for all release heights from 50 to 300 m. The listed values apply to a 500-m plant boundary.

[c]88.5-km radius.

summary tables that list (in addition to other statistics) the fly-ash collection efficiencies and the stack heights for the various coal-fired steam plants.

Emission regulations for coal-fired steam plants set by the EPA require that the emission not be greater than 0.1 lb of particulates (i.e., fly ash) per million Btu of fuel (32). This number would correspond to a release to the atmosphere of about 1 percent of the total ash in the coal burned, the value used in estimating the airborne radioactive releases from the model coal-fired steam plan from which the dose commitments were calculated in this paper. Utilities are upgrading and backfitting their plants to meet this standard, but it will be some time before it is achieved throughout the industry.

7. SUMMARY AND CONCLUSIONS

The radiological impact of naturally occurring radionuclides emitted in the airborne effluent of a model advanced 1000-MW(e) coal-fired steam plant, burning coal containing 1 ppm uranium and 2 ppm thorium and releasing to the atmosphere 1 percent of the total ash in the coal, was evaluated and compared with the impact of the radioactive materials in the airborne effluents of model 1000-MW(e) light-water reactors. Computer codes developed at the 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 plant and the nuclear plants was ingestion of contaminated foodstuffs. For the nuclear plants, the pathway via immersion in the airborne effluents was also significant.

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 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 of 10 CFR 50, Appendix I.

The maximum individual dose commitments from the model coal plant were greater than those from the pressurized-water reactor (PWR), except for thyroid dose, but were less than those from the boiling-water reactor (BWR), except for the bone dose. In general, however, whole-body and all organ doses for both the coal and nuclear plants were within the same order of magnitude. The estimated 50-year dose commitments to the whole body in millirems per year of plant operation were: coal plant - 1.9; BWR - 4.6; and PWR - 1.8. Whole-body and organ population dose commitments within a radius of 88.5 km (55 miles) ranged in all cases from 50 percent higher to several times higher for the coal plant than for the nuclear plants except for thyroid dose from the BWR, which was 50 to 100 percent higher than the thyroid dose from the coal plant. The estimated whole-body population dose commitments in man-rem were: coal plant - 21 (100-m stack); BWR - 13; and PWR - 13. For bone dose, the values in man-rem were: coal plant - 225; BWR - 21; and PWR - 20. In making these estimates, it is assumed that 100 percent of the food is grown and consumed at the reference point for the dose calculation. If the amount of food grown and consumed locally is reduced from 100 to 0 percent, the population doses for whole-body exposures in man-rem are: coal plant - 1.2; BWR - 4.3; and PWR - 3.1. For bone doses, the values are: coal plant - 31; BWR - 5.7; and PWR - 4.9.

The assumed release to the atmosphere of 1 percent of the total ash in the coal burned approximates the EPA regulations 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. Uranium and thorium concentrations in coal higher than the 1 ppm and 2 ppm, respectively, assumed for the present evaluation are common. The use of coal containing higher uranium and thorium concentrations and higher ash releases could result in dose commitments several orders of magnitude higher than those calculated. Methods for estimating these higher dose commitments are presented.

The release of naturally occurring radioactivity from coal-fired power plants is in addition to the release of other toxic materials (5). The results of our study show that a complete analysis comparing the environmental effects of coal-burning power plants versus nuclear power plants should include the radiological impacts from both types of plants.

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