The inner (about 1832) moraine contained no large boulders and few rocks which were not partly rounded at their edges. This suggests the rocks of the inner moraine were the result of the glacial erosion which occurred in the 120 years (about) between the first and second ice advance. The large volume of material in the 1832 moraine is further possible evidence that the ice advance at that time followed a century of ice action on the mountain slopes. Examination of the size, shape, and numbers of large boulders in moraines of other glaciated areas in which there were ice advances during the "Little Ice Age" would be helpful in substantiating the use of boulders as an aid in chronological studies.

J. ROGER BRAY

Grasslands Division, Department of Scientific and Industrial Research, Palmerston North, New Zealand

References and Notes

1. Peter Read, Kelowna, B.C., personal communication.
2. J. R. Bray and G. J. Struik, *Canad. J. Botany* **41**, 1245 (1963).
3. I thank Dr. M. E. Hale for the lichen identification and Mr. and Mrs. G. Hartley and Mr. and Mrs. P. Read for aid in measuring the distance of ice retreat.

1 January 1964

Radioactivity in the Atmospheric Effluents of Power Plants That Use Fossil Fuels

Abstract. *Analysis of the fly ash produced by combustion of pulverized Appalachian coal has shown that a 1000-megawatt coal-burning power plant will discharge into the atmosphere from about 28 millicuries to nearly 1 curie per year of radium-226 and radium-228. An oil-burning plant of similar size will discharge about 0.5 millicurie of radium per year. Comparison of these data with data on the release of fission products from nuclear-powered generating stations shows that when the physical and biological properties of the various radionuclides are taken into consideration, the conventional fossil-fueled plants discharge relatively greater quantities of radioactive materials into the atmosphere than nuclear-powered plants of comparable size.*

Our interest in the distribution of naturally occurring radionuclides has led us to analyze samples of ash from coal and oil consumed in the production of electrical energy. Six samples of fly ash were obtained from the electrostatic precipitators of boilers burning six different batches of pulverized semibituminous coal from Appalachian mines. In addition, three samples of the solid residues formed when fuel oil was burned were obtained from the breechings of smoke stacks carrying the combustion products from boilers fired with South American oil. These ash samples were analyzed radiochemically for the radionuclides Ra^{226}, Ra^{228}, and Th^{228} by methods adapted from those of Petrow *et al.* (*1*).

The results of these analyses are shown in Table 1. It is interesting that for coal ash, the near equality of the Ra^{228} and Th^{228} content indicates that secular equilibrium exists and that the levels of activity for both nuclides must be supported by an equivalent amount of Th^{232} activity. However, for petroleum ash, the ratio of Th^{228} to Ra^{228} is 1.4, near the value of 1.5 which would be expected for transient equilibrium supported by a Ra^{228} parent. The data indicate that for coal, the whole thorium series is contained within the matrix whereas, for petroleum, radium has been leached selectively from the substrate.

Large, coal-burning central power stations burn pulverized coal, the combustion products of which, both gaseous and particulate, are discharged into the atmosphere through smoke stacks. In the plants from which our samples were obtained, mechanical filters and electrostatic precipitators are used to reduce the fly-ash content of the exhaust gases, and it is estimated that 97.5 percent of the fly ash produced is thus collected when the equipment is properly maintained. The remaining 2.5 percent is discharged directly into the atmosphere. For the purpose of this report, it was assumed that the fly ash so collected is representative of the chemical composition of the dust that passes into the atmosphere.

A 1000-megawatt power station will consume about 2.3 million tons of semibituminous coal per year (*2*). If we assume that the coal has an ash content of 9 percent, of which 2½ percent is discharged into the atmosphere, it can be calculated that such a coal-burning station will discharge about 4.5×10^9 g of fly ash into the atmosphere each year. On the basis of our analytical data, this fly ash will contain about 10.8 mc of Ra^{228} and 17.2 mc of Ra^{226}.

In coal ash, the radioisotopes originate from traces of U^{238} and Th^{232}. On the basis of the measured Ra^{226} and Ra^{228} content of the ash, and with the assumption that the coal has a 9-percent ash content, U^{238} and Th^{232} are present in coal in concentrations of 1.1 and 2.0 parts per million, respectively. The activity of U^{238} is 0.4 pc/g, while that of Th^{232} is about 0.2 pc/g. Anderson reported comparable concentrations of Ra^{226} in British coal (*3*).

A power station in which dust collection equipment is not used will discharge about 80 percent of the ash into the atmosphere. If such a plant has a capacity of 1000 Mw, it will annually discharge about 350 mc of Ra^{228} and 550 mc of Ra^{226}.

Oil-burning plants normally discharge nearly all of the combustion products into the atmosphere. A 1000-Mw station will consume about 460 million gallons of oil per year. If it is assumed that the oil has an ash content of 0.05 percent a total of 7.3×10^8 g of fume will be discharged, the total radium content (Ra^{226} plus Ra^{228}) of which would be about 0.5 mc (Table 1).

The amounts of radium just mentioned, and the associated radionuclides of the uranium and thorium series do not add significantly to the other sources of natural radioactivity to which humans are exposed. Because of the insolubility of fly ash, one would expect that radium inhaled in fly ash would be present in higher concentrations in the lungs than in other soft tissues. The lungs from three adult New York City residents were found to contain, 1.0, 1.2, and 1.0 pc of Ra^{228}, 0.8, 0.7, and 0.7 pc of Th^{228}, and 0.2, 0.2, and 0.5 pc of Ra^{226}. Data on the radium content for other soft tissues are not available in New York City but Hursh *et al.* (*4*) have reported that the concentration of Ra^{226} in soft tissues other than lung, in subjects from Rochester, N.Y., ranges from 0.05 to 0.1 pc/kg, wet weight, compared to a mean of 0.3 pc/kg wet weight in the lungs of our subjects. In contrast, the normal concentrations of Ra^{226} in bone was reported by Hursh to be 3.4 pc/kg wet weight. The radium in bone is due primarily to the normal occurrence of this element in soil (*5*) from which it passes metabolically into plants and animals.

Table 1. Radium-thorium content of fuel residues.

No. of sample	Ra^{226} (pc/g)	Ra^{228} (pc/g)	Th^{228} (pc/g)
	Coal ash		
1	5.0	1.9	2.5
2	4.2	2.5	2.7
3	3.8	2.6	2.4
4	2.8	1.8	2.1
5	4.8	2.7	2.4
6	2.1	3.1	3.3
Mean	3.8 ± 0.4	2.4 ± 0.4	2.6 ± 0.4
	Petroleum ash		
1	0.14	0.45	0.67
2	0.18	0.32	0.52
3	0.30	0.70	0.83
Mean	0.21±0.07	0.49±0.16	0.68±0.13

Samples of dust collected from the atmosphere of New York City were also analyzed. The dust contained in a 26,000-m^3 sample of air collected continuously during the month of December 1962 was found to contain, 1.5×10^{-4} pc/m^3, 0.8×10^{-4} pc/m^3, and 1.5×10^{-4} pc/m^3 of Th^{228}, Ra^{226}, and Ra^{228}, respectively. A person breathing 20 m^3 of air in 24 hours would thus inhale about 0.0046 pc of Ra^{226} plus Ra^{228} per day. This is a very small fraction of the radium ingested daily in food.

It is of interest to compare the quantities of natural radioactivity discharged by coal-burning plants with the quantities of radioactive substances discharged into the atmosphere by electrical generating stations that utilize nuclear energy as the source of heat. In order to make such a comparison it is necessary to find a method that makes it possible to compare radionuclides that have varying chemical, physical, and biological properties. The potential hazard of a radionuclide depends on many factors, including metabolic properties, half-life, and decay schemes. These factors are all taken into consideration in computing the maximum permissible concentration of a given radionuclide (*6*), and the relative significance of radioactive substances discharged into the atmosphere can therefore be compared if their maximum permissible concentrations are known.

Table 2. Comparisons of maximum permissible concentrations of certain radionuclides in air (*6*).

Nuclide	Half-life	Max. perm. conc.* ($\mu c/cm^3$)
Ra^{226}†	1620 years	0.5×10^{-11}
Ra^{228}†	5.7 years	1×10^{-11}
Kr^{85}	10.8 years	3×10^{-6}
I^{131}	8 days	3×10^{-9}

* The listed values are for 168 hours of continuous exposure. They are not intended to be used for exposure of the general population, but these values are applicable to our purposes since we are interested in their ratios. It is generally considered desirable to divide the values recommended by the International Commission on Radiation Protection by 10 when applying them to the general population. † Assumed to be in the insoluble form.

In Table 2 are listed the maximum permissible concentrations of Ra^{226} and Ra^{228}, and I^{131} and Kr^{85}, the two principal radionuclides present in the atmospheric effluents of reactors. The maximum permissible concentrations of Kr^{85} and I^{131} are much higher than the permissible concentrations for the radium isotopes. This is because of a combination of factors, among which are (i) radium isotopes give rise to a number of radioactive daughters, (ii) some of the isotopes in the decay chains emit alpha particles, and (iii) the radium isotopes are relatively long-lived and their energies are greater than those associated with the decay of Kr^{85} or I^{131}.

A 1000-Mw coal-burning plant having good fly ash control equipment will, as noted earlier, annually discharge about 28 mc of mixed radium isotopes into the atmosphere. From the ratios of the maximum permissible concentrations, 1 mc of radium, consisting of equal parts of Ra^{226} and Ra^{228}, is radiobiologically comparable, approximately, to 400,000 mc of Kr^{85} and 400 mc of I^{131}. The atmospheric effluents from a well-operated plant of this size thus contains naturally occurring radioactive substances equivalent, from the point of view of their hygienic significance, to about 10^4 c of Kr^{85} and 10 c of I^{131}. Plants that burn pulverized coal but which do not provide mechanical or electrical dust separators discharge radium in far greater amounts. Such a plant might discharge about 1 c/yr of mixed radium isotopes. This is equivalent to more than 4×10^5 c of Kr^{85} or more than 400 c of I^{131}. An oil-burning plant of 1000-Mw electrical generating capacity would discharge an amount of radium that is approximately equivalent to 200 c of Kr^{85} and 200 mc of I^{131}.

Conventional practice in the operation of nuclear reactors provides means for storing the waste gases so as to permit the short-lived radionuclides to decay. In most plants the waste gases can be stored sufficiently long to permit all the radioiodine to decay, leaving only the Kr^{85} to be discharged. The amounts of krypton actually available for discharge are miniscule and do not approach the amounts of this radionuclide equivalent to the amounts of radium discharged by fossil plants. For example, during 1961, the Yankee Nuclear Power Station at Rowe, Massachusetts, discharged only 1.9 mc of gaseous wastes into the atmosphere (*7*). This experience is consistent with that of other nuclear powered electrical generation stations in the United States.

Our measurements of the natural radioactivity of fossil fuels have thus led us to the conclusion that an electrical generating station that derives its thermal energy from such fuels discharges relatively greater quantities of radioactive substances into the atmosphere than many power plants that derive their heat from nuclear energy.

MERRIL EISENBUD
HENRY G. PETROW
Institute of Industrial Medicine, New York University Medical Center, New York

References and Notes

1. H. Petrow and R. Allen, *Anal. Chem.* **33**, 1303 (1961); H. Petrow and R. Lindstrom, *ibid.*, p. 313; H. Petrow, B. Sohn, R. Allen, *ibid.*, p. 1301.
2. The authors are indebted to the staff of the Consolidated Edison Company of New York for various enginering data use in the calculations. The samples of fly ash and oil sludge were also provided by the Consolidated Edison Company.
3. E. Anderson, W. V. Mayneord, R. C. Turner, *Nature* **174**, 424 (1954).
4. J. B. Hursh, A. Lovaas, E. Blitz, Univ. of Rochester, Report UR-581, 31 Oct. 1960.
5. M. Eisenbud, *Environmental Radioactivity* (McGraw-Hill, New York, 1963).
6. International Commission on Radiation Protection, "Report of Committee II on permissible dose of internal radiation," *Health Phys.* **3**, 1 (1960).
7. J. F. Kaslow, *Nucl. Safety* **4**, 96 (1962).
8. This research was supported in part by the Division of Biology and Medicine of the U.S. Atomic Energy Commission under contract AT(30–1)2896.

6 March 1964

Amethyst: Optical Properties and Paramagnetic Resonance

Abstract. *Color centers in amethyst are produced by the action of ionizing radiation on precursor centers that arise from substitution of Fe^{+3} for Si^{+4} in the α-quartz structure. These Fe^{+3} centers provide the dominant features of the electron paramagnetic resonance spectrum of amethyst. The three equivalent Si^{+4} sites are unequally occupied by Fe^{+3}, a circumstance that explains the optical biaxiality of amethyst.*

The origin of color in amethyst, a form of α-quartz, has excited attention for centuries. We have accumulated evidence that color centers are gener-