

IONIZING RADIATION: SOURCES AND BIOLOGICAL EFFECTS

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on the Effects of Atomic Radiation

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NOTE

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ANNEX C

Technologically modified exposures to natural radiation

CONTENTS

	<i>Paragraphs</i>		<i>Paragraphs</i>
<i>INTRODUCTION</i>	1-4		
I. RADIATION EXPOSURES DUE TO COAL-FIRED POWER PLANTS	5-33		
A. Source terms	5-19		
1. Activity concentrations in coal	9		
2. Activity concentrations in ash	10-15		
3. Atmospheric discharges	16-19		
B. Environmental levels and doses	20-31		
C. Other sources of radiation exposure resulting from the use of coal	32-33		
II. RADIATION EXPOSURES DUE TO GEOTHERMAL ENERGY PRODUCTION	34-35		
III. RADIATION EXPOSURES DUE TO EXPLOITATION OF PHOSPHATE ROCK	36-80		
A. Doses arising from effluent discharges	38-55		
1. Effluents from phosphate rock processing operations	39-40		
2. Effluents from phosphoric acid plants	41-44		
3. Effluents from uranium recovery operations	45-46		
4. Environmental concentrations and doses	47-55		
B. Doses arising from the use of phosphate fertilizers	56-65		
		C. Doses arising from the use of by-products and wastes	66-77
		D. Recapitulation	78-80
		IV. ENHANCED INDOOR EXPOSURES	81-91
		V. ENHANCED EXPOSURES TO COSMIC RAYS	92-99
		A. Passengers in aircraft	92-96
		B. Astronauts	97-99
		VI. MISCELLANEOUS SOURCES OF RADIATION	100-135
		A. Consumer products	101-131
		1. Radioluminous products	103-116
		2. Electronic and electrical devices	117-118
		3. Antistatic devices	119-122
		4. Smoke detectors	123-125
		5. Ceramic, glassware, alloys, etc., containing uranium or thorium	126-131
		B. Other miscellaneous sources of radiation	132-135
		VII. SUMMARY	136-137
		<i>References</i>	<i>Page</i> 137

Introduction

1. There are circumstances where man finds himself in a natural radiation environment to which he would not be exposed if some kind of technology had not been developed. Examples are travelling by air, using natural gas for cooking or heating purposes, living in the neighbourhood of a coal-fired power plant. The resulting exposures have been labelled "technologically enhanced" natural radiation exposures by Gesell and Prichard [G1], who defined them as exposures to truly natural sources of radiation (that is, naturally-occurring

radionuclides and cosmic radiation) which would not occur without (or which are increased by) some technological activity not expressly designed to produce radiation.

2. In some cases, technology helps to reduce the natural radiation exposure. For example, when drinking water supplies are drawn from surface waters, the use of water-purification processes brings about a decrease in the concentration of radium and other naturally-occurring radioactive elements. Another example is the burning of fossil fuel, which reduces the

specific activity of ^{14}C in the biosphere and therefore lowers the doses from that radionuclide. This Annex deals with "technologically modified" exposures to natural radiation and presents some assessments of the doses arising from such exposures.

3. The Committee recognizes that the definition given in paragraph 1 is not rigorous and that, in reality, radiation is either natural or artificial in origin. It also realizes, however, that there has been scientific interest in recent years in radiation exposure from the variety of sources which will be discussed in this Annex. The Committee believes that consideration of these sources in a separate Annex is justified at least for this report.

4. Although they do not properly fall within the above definition, there are a number of other sources of exposure to radiation which are a direct consequence of man's technological activities, and which are included for convenience within this Annex. Examples of these are consumer products incorporating radionuclides, and electronic and electrical devices. Other man-made sources of exposure such as the explosion of nuclear devices and the operation of nuclear power plants are discussed in Annexes E and F, respectively.

I. RADIATION EXPOSURES DUE TO COAL-FIRED POWER PLANTS

A. SOURCE TERMS

5. Coal, like most materials found in nature, contains trace quantities of the naturally-occurring primordial radionuclides. Therefore, the combustion of coal results in the release to the environment of some natural activity and in the re-distribution of that natural activity from deep in the earth to locations where it can modify ambient radiation fields and population radiation exposures.

6. The annual world production of coal (including brown coal and lignite) was about $3.7 \cdot 10^{12}$ kg in 1979 [U5], the main producers being China, the Union of Soviet Socialist Republics, and the United States of America. Coal is used most commonly for industrial purposes, power generation, and space heating. In 1974, about 70% of the coal consumed in the United States was burnt in electric power stations, while only 2% was used for space heating in household and commercial markets [U3]. The situation may however be quite different in other countries. In Poland, for example, about 15% of the coal consumed in 1976 was burned as household fuel [G10].

7. In view of the importance of coal for generating electricity, this section will deal essentially with the radiation exposures arising from its use to produce electric power. Most documented exposures are those due to the atmospheric releases of gases and particulates from power stations. There is more particulate emission during combustion of coal than of any other fuel because of its high ash content; for example, the ash content of coal burned in the United States in power plants with a capacity of more than 25 MW(e) ranged from 4 to 25% in 1977 [W10]. The combustion of about $3 \cdot 10^9$ kg of coal is required to produce an electrical energy of 1 GW a [B1, E1, K1, K2].

8. The activities of natural radionuclides discharged in the atmosphere from a power plant per unit electrical energy produced depend on a number of factors such

as the activity concentrations in coal, the ash content of the coal, the temperature of combustion, and the efficiency of the filtering system. Marked differences should therefore be expected between the measured activities discharged per unit energy produced from different power plants. The currently available information on the activity concentrations in coal and ash and on the atmospheric discharges will be briefly reviewed.

1. Activity concentrations in coal

9. Since the publication of the 1977 report of UNSCEAR [U2], a substantial number of publications have dealt with the measurement of activity concentrations of natural radionuclides in coal. Table 1 presents results of measurements of radionuclides in coal samples originating from mines or from power plants. The most significant study is that of Beck et al. [B2], who listed the concentrations measured in almost 1000 samples obtained directly from mines providing most of the coal presently used in the United States. These authors found that the activity concentrations measured in the coal samples varied over two orders of magnitude (0.7 to 70 Bq kg⁻¹ for ^{40}K , less than 3 to 520 Bq kg⁻¹ for ^{238}U , and 3 to 320 Bq kg⁻¹ for ^{232}Th). Variations can be quite large even in the same area. Gluskoter et al. [G2] obtained concentrations ranging from 4 to 300 Bq kg⁻¹ for ^{238}U , 0.4 to 10 Bq kg⁻¹ for ^{232}Th and 3 to 100 Bq kg⁻¹ for ^{40}K in five different seams of coal mined in Illinois. In general, the concentrations of natural radionuclides in coal are less than those in the earth's crust. Occasionally, however, usually as a result of leaching from abnormally radioactive overburdens of volcanic origin, very high concentrations of some radionuclides, in particular uranium, can be found in various coal deposits. Those uraniumiferous coals are the exception and occur almost invariably in low grade coal deposits [A1, D1, V1, V2]. It will be assumed in this Annex that the average activity concentrations in coal are 50 Bq kg⁻¹ of ^{40}K and 20 Bq kg⁻¹ each of ^{238}U and ^{232}Th and that all the decay products of ^{238}U and of ^{232}Th are in radioactive equilibrium with their precursors, although that might not be always the case for ^{210}Pb and ^{210}Po (see for example the results of Kaakinen et al. [K1] in Table 1). Enhanced activity concentrations of ^{210}Pb could conceivably occur if large quantities of ^{222}Rn diffuse from adjacent high activity rocks into a lower activity coal seam with subsequent trapping of the decay products in the coal [B2].

2. Activity concentrations in ash

10. In the production of electric power, coal is burned in furnaces operating at temperatures of up to 1700° C. Most of the mineral matter in the coal is fused into a vitrified ash. A portion of the heavier ash, along with incompletely burned organic matter, drops to the bottom of the furnace as bottom ash or slag. The fly-ash, however, is carried through the boiler along with the hot flue gases and any volatilized mineral compounds to the stack where, depending on the efficiency of emission control devices, some fraction is collected while the rest (escaping fly-ash) is released to the atmosphere [B2].

11. The radionuclides included in the non-combustible mineral matter are thus partitioned between the bottom ash and fly-ash, except for the gases and volati-

lized minerals which will be incorporated directly into the flue gases. Table 2 presents a list of reported activity concentrations of natural radionuclides in bottom ash, collected fly-ash and escaping fly-ash. Owing mainly to the elimination of the organic component of the coal, there is very approximately an order of magnitude enhancement of the activity concentrations from coal to ash. Consequently, the natural radionuclide concentrations in ashes and slags from coal-fired power stations are significantly higher than the corresponding concentrations in the earth's crust [L4]. The arithmetic averages of the concentrations in escaping fly-ash from Table 2 are, in Bq kg⁻¹, 265 for ⁴⁰K, 200 for ²³⁸U, 240 for ²²⁶Ra, 930 for ²¹⁰Pb, 1700 for ²¹⁰Po, 70 for ²³²Th, 110 for ²²⁸Th and 130 for ²²⁸Ra.

12. In the United States, a number of recent studies have aimed at understanding the mechanisms of aerosol formation in the coal-fired power plants [C1, K1, K2, K3, L1, N2, O1, R1]. It has been observed that certain trace elements partition unequally between bottom ash and fly-ash. They become concentrated on the smaller fly-ash particles which have larger surface-to-volume ratios as the hot flue gases cool down on their way to the stack [K1, K2, L1, N2, R1]. This process results in the depletion of certain elements in bottom ash and their consequent enrichment in fly-ash, an effect which increases as the size of the fly-ash particles decreases [C1, L1, N2]. These smaller particles are less efficiently collected by emission control devices such as electrostatic precipitators and scrubbers, and thus preferentially escape from the plant.

13. The apparent enrichment of some radionuclides in escaping fly-ash particles can be characterized by the enrichment factor EF, defined as the ratio of the concentrations of the radionuclide (X) and of ⁴⁰K in the sample divided by the corresponding ratio in coal:

$$EF = \frac{(X) \text{ sample} / (^{40}\text{K}) \text{ sample}}{(X) \text{ coal} / (^{40}\text{K}) \text{ coal}} \quad (1)$$

Potassium-40 is used as a reference because its activity concentration remains more or less constant in all types of ash in a given plant and thus is assumed to be a tracer for the aluminosilicate dominated ash matrix [C1]. Figure 1 shows the variation of the enrichment factors of ²³⁸U, ²²⁶Ra, ²²⁸Ra, ²¹⁰Pb and ²²⁸Th as a function of the size of the escaping fly-ash [C1]. The enrichment factors given in that figure are derived from measurements of samples obtained at a power plant equipped with Venturi scrubbers and electrostatic precipitators [C1]. The escaping fly-ash was collected by a large cyclone separator; the four fractions obtained had measured mass median diameters of 18.5, 6.0, 3.7, and 2.4 μm and count median diameters of 2.7, 2.6, 1.1, and 0.9 μm, respectively [F6]. Among the radionuclides measured by Coles et al. [C1], the most enriched was ²¹⁰Pb, followed by ²³⁸U, ²²⁶Ra, ²²⁸Ra and ²²⁸Th. It is likely that a large fraction of ²¹⁰Pb and ²¹⁰Po volatilizes during the combustion, then condenses somewhere down the flue line on the finer fly-ash particles, whereas ⁴⁰K and isotopes of thorium melt with the aluminosilicate minerals and drop out as bottom ash or coalesce and are carried through the flue line as fly-ash particles. According to Coles et al. [C1], the uranium isotopes could behave in either way according to their mineralogical or chemical form in the coal; the uranium that is associated with the clays, or which is mineralized as coffinite, would remain with the bottom ash whereas the uranium that is dispersed in the coal as uraninite could become volatile as UO₃ and later condense on the

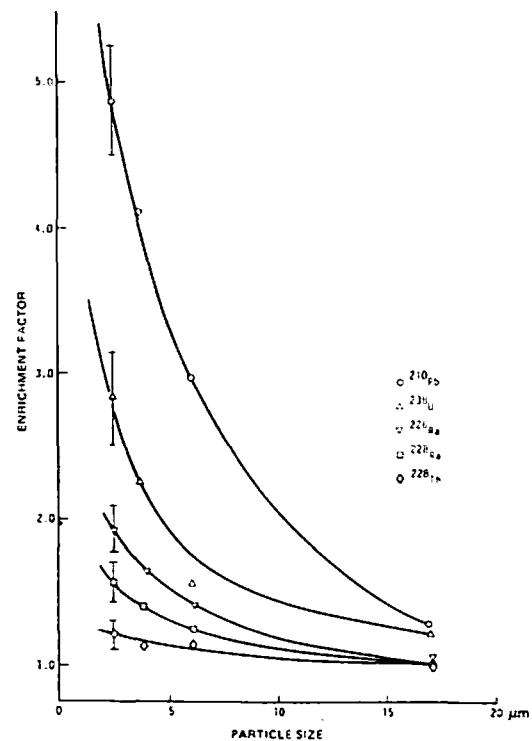
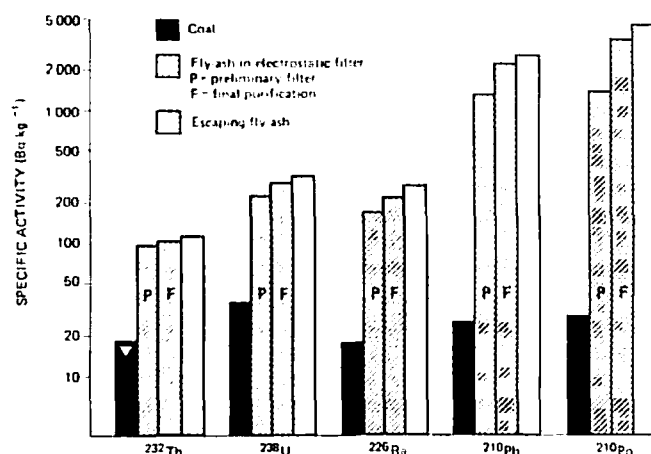


Figure 1. Enrichment factors of ²¹⁰Pb, ²³⁸U, ²²⁶Ra, ²²⁸Ra and ²²⁸Th versus size (mass median diameter) in stack fly-ash collected downstream from an electrostatic precipitator [C1]

fly-ash particles [C1]. As a decay product of ²³⁸U, ²²⁶Ra would behave in an analogous manner; on the other hand, ²²⁸Ra, as a decay product of ²³²Th, would tend to be associated with the matrix of the fly-ash particles.

14. The mechanisms described above are supported by evidence from studies of fly-ash particles which show that they consist of an insoluble matrix composed mainly of iron and aluminium silicates coated with a layer of soluble compounds [K3, L1, P3]. However, other physical-chemical processes such as segregation (diffusive transport to the surface of the particle) and gas-surface reactions may also contribute to the surface enrichment of the ash particles [S11]. Table 3 presents published enrichment factors, which may or may not use ⁴⁰K as a reference, while Figure 11, extracted from a study made in the Federal Republic of Germany, illustrates the increase in specific activity as one proceeds from one stage of particle retention to the next [C5, J7]. As expected, the enrichment factors are higher for ²¹⁰Pb and ²¹⁰Po (range of 1 to 11) than for uranium, radium or thorium (range of 1 to 2). As a general rule, the values of the enrichment factors increase with the temperature of combustion and decrease with the particle size, at least for sizes above 1 μm.

15. Measurements of the size distribution of escaping fly-ash particles are very few. In the Federal Republic of Germany, a nearly log-normal size distribution has been found with an activity median aerodynamic diameter of 3–5 μm for uranium, thorium and radium, and of about 1 μm for ²¹⁰Pb and ²¹⁰Po [J7]. In the United States, the size distribution of particles collected in a plant down-stream from an electrostatic precipitator has been found to be bimodal, the two modes being at 0.06 and 0.5 μm [O1]. A similar size distribution, with two modes at 0.04 and 0.25 μm, has been observed in the plume of a coal-fired power plant [P3]. The mass activity concentration of enriched radionu-



600 MW LIGNITE POWER PLANT (with dry firing, approx. 1100°C)

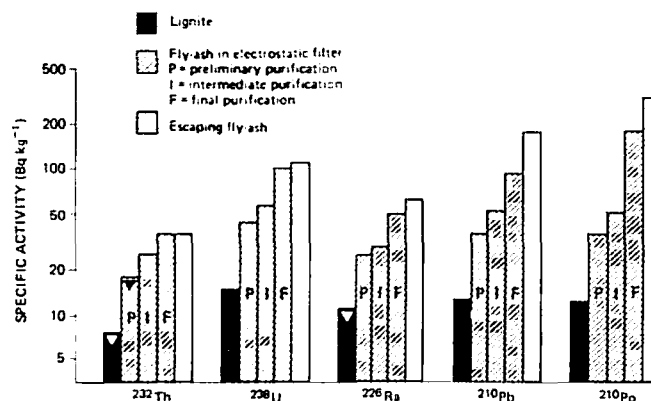


Figure II. Measured mean values of specific activity in the coal, in the fly-ash deposited in the electrostatic filter stages and in the escaping fly-ash [C5]

lides, such as ²¹⁰Pb and ²¹⁰Po, may be much higher in those small particles than suggested by the values given in Table 3 and Figure I [N2, O1]. However, an analysis of the submicron particles with respect to the concentrations of elements volatilized during combustion has shown these concentrations to be independent of particle size, in contrast to the larger particle sizes where an inverse relationship with particle size applies [S12]. These results would be consistent with a mechanism for formation of submicron particles involving "bursting" of larger particles due to gas release during rapid heating, followed by coagulation and condensation of volatilized elements to form particles in the 0.1–1.0 μm size range [S12].

3. Atmospheric discharges

16. The atmospheric discharges of natural radionuclides are obtained as the products of the mass of fly-ash released per unit of energy produced by the activity concentrations in escaping fly-ash. The mass of fly-ash released per unit of energy produced depends heavily on the efficiency of the particulate control. In the United States, the average atmospheric releases in 1972 from 696 major steam plants amounted to about 8% of the total ash in the coal burned [M3, F5]. However, all plants in the United States must eventually meet the clean air standards of the Environmental Protection Agency which are set at $1.4 \cdot 10^6$ kg of ash per GW a of electricity generated [M3], which corresponds to a

release of about 1% of the total ash. The average releases in that country are thus likely to lie at present between those two values. In the Federal Republic of Germany, the emission of dust is limited by the legal authorities at 0.15 g per m³ of flue gas, which corresponds to a release of about 1% of the total ash [S1]. In Italy, typical coal-fired power plants are equipped with electrostatic precipitators allowing an ash retention of 95%, and thus a release of 5% [M1]. In Poland, the fraction of ash released is estimated at 20% [J4], while in India it has been assumed to be 10% [M12]. With regard to the USSR, it has been reported that the modern coal-fired power stations are equipped with electrofilters allowing an ash retention of 98.5–99%. However, there are other power stations for which the efficiency of retention of the fly-ash particles is about 90%, corresponding to an atmospheric discharge of about 10% of the ash produced. So the power plants which have the same power as the Zaporozhje station (1.2 GW(e)) and an ash retention efficiency of 90%, burning $3.4 \cdot 10^6$ tonnes of coal with a high ash content (35–40%), discharge about $1.3 \cdot 10^5$ tonnes of ash to the atmosphere annually [K11, 11, 15].

17. It thus seems that by and large there are two types of coal-fired power plants throughout the world, namely those which release about 10% of the total ash produced and those, equipped with sophisticated retention devices, which release only about 1% of the ash. Although it would probably be more realistic to estimate the radiation impact resulting from the releases

of the two types of plants, it has been decided in this Annex to derive only one set of activities discharged per unit of energy produced.

18. Table 4 presents the estimates of atmospheric discharges adopted in Annex B of the 1977 report of UNSCEAR [U2] and other estimates which originate mainly from highly industrialized countries and were published after the preparation of the 1977 report. On this basis, "average" discharges have been estimated for the purpose of assessing the doses arising from coal combustion in power plants. Those "average" atmospheric discharges per unit energy generated are also presented in Table 4; in terms of MBq (GW a)⁻¹, they amount to 4000 for ⁴⁰K, 1500 for ²³⁸U through ²²⁶Ra, 5000 for ²¹⁰Pb and ²¹⁰Po, and 1500 for the radionuclides of the ²³²Th decay series, from ²³²Th to ²²⁴Ra. These normalized discharges are taken to be representative of the current situation on the world-wide scale. For the purpose of comparison with the values given in the previous paragraphs, it can be calculated that they correspond, for example, to a plant burning coal with a 10% ash content and equipped with a filtering system allowing an ash retention of 97.5%, the enrichment factors would be 1 for ⁴⁰K, the isotopes of radium, uranium and thorium, and 3 for ²¹⁰Pb and ²¹⁰Po.

19. Releases of ²²²Rn and of ²²⁰Rn have to be estimated separately as radon is not collected by the particulate control devices. The activities of ²²²Rn and ²²⁰Rn released per GW a have been assessed at 60 GBq on the basis of the following assumptions: ²²²Rn and ²²⁰Rn are in radioactive equilibrium with ²³⁸U and ²³²Th, respectively, in coal and are discharged in their entirety when coal is burned; the average activity concentration of ²³⁸U or ²³²Th in coal is 20 Bq kg⁻¹; and the combustion of 3 10⁹ kg of coal is required to produce 1 GW a of electrical energy.

B. ENVIRONMENTAL LEVELS AND DOSES

20. Measurements in surface air, carried out about ten years ago, had clearly shown the presence of enhanced concentrations of the natural radionuclides precursors of the radon isotopes. Bedrosian et al. [B3] measured downwind of a coal power plant in Alabama, concentrations of up to 50 μBq m⁻³ of ²²⁶Ra, 10 μBq m⁻³ of ²³²Th and 100 μBq m⁻³ of ²³⁸U, compared with the "normal" concentrations of about 1 μBq m⁻³ for each of the three radionuclides. However, recent measurements [F2, S2, T3] have failed to reveal a significant increase in the surface air concentrations around the plant. This is probably due to the fact that the activities discharged are smaller now than what they used to be; another reason is the taller stacks which result in a much greater atmospheric dilution [B2].

21. Snow, which can be expected to have a low background concentration of the natural radionuclides considered, was sampled by Jaworowski et al. [J5] around coal-fired power plants. The measured ²²⁶Ra concentrations ranged up to 60 mBq kg⁻¹ and were related to the distance from the power plants. In addition, studies of a glacier 150 km away from a Polish industrial centre have revealed a 50-fold increase in ²²⁶Ra concentration over the preceding 80 years [J5].

22. Since the concentrations in fly-ash are on average a few times higher than the corresponding concentrations in soil, and since the activity deposited remains for a relatively long period of time in a thin superficial

layer of soil, measurements in soil have been conducted by several investigators. In Poland, the concentrations of uranium, thorium, and ²²⁶Ra were found to be higher in the upper 5 cm layer than in the 5–10 cm layer of soils of industrial areas, while this effect was not observed in rural soils [J2]. In the United States, Beck et al. [B2] attempted to detect increases in natural radionuclide concentrations in surface layers of soil in the environs of three large coal-fired power plants, but only obtained positive results for the oldest and most poorly controlled of the three plants. Other recent studies [F2, S2] have also been unsuccessful. The annual enhancement in the concentrations of ²³⁸Th, ²²⁶Ra and ⁴⁰K in the upper 30 cm layer of soil within 20 km of coal-fired power stations has been theoretically estimated in a study of the USSR to represent, on average, only 0.08%, 0.12%, and 0.03% of the corresponding typical natural concentrations in soil [L4].

23. The main pathways through which the populations living around coal-fired power plants are exposed to enhanced levels of natural radionuclides are inhalation during the passage of the cloud, and external irradiation, inhalation and ingestion resulting from the activity deposited on the ground.

24. The collective dose commitments due to inhalation during the passage of the cloud have been roughly estimated as follows. Assuming that there is no decay during the atmospheric transport, all the activity released A₀ (Bq) will eventually be deposited on a surface S (m²). The average activity density is A₀/S (Bq m⁻²) and corresponds to an integrated atmospheric concentration at ground level of A₀/S v_d (Bq s m⁻³), where v_d is the deposition velocity. The collective dose commitment M_q^c in organ or tissue q is given by:

$$M_q^c = \frac{A_0}{v_d S} S \delta_N B \frac{D_q}{I_{ih}} \quad (2)$$

where v_d = 10⁻² m s⁻¹, value which takes into account both dry and wet deposition; Sδ_N is the population affected, which is the product of the area of the deposition region S and of the population density δ_N, assumed to be uniform and equal to 10⁻⁴ m⁻² around the plant. The areal dependence is removed by the product of the quantities A₀/v_dS and Sδ_N; B is the individual adult breathing rate, taken to be equal to 2.3 10⁻⁴ m³ s⁻¹; D_q/I_{ih} is the committed absorbed dose in organ or tissue q per unit activity inhaled (Gy Bq⁻¹). In this assessment, the values adopted have been derived from those calculated by Jacobi [J7] using a quality factor of 20 for α particles (Table 5). These figures were estimated assuming that the radionuclide content of the particles was 80% insoluble and 20% soluble and using ICRP dosimetry [16]. No account is taken of the possible reduction of the atmospheric concentration indoors.

25. This method was used to calculate the collective dose commitments during the passage of the cloud for most of the natural radionuclides, one notable exception being ²²²Rn and its short-lived decay products. In that case, the activity A₀ of radon distributed over a surface S of land was compared to the quotient of the atmospheric concentration and of the natural emanation rate for ²²²Rn. One obtains

$$M_q^c = \frac{A_0}{S} \frac{1.8 \text{ (Bq m}^{-3}\text{)}}{2 \cdot 10^{-2} \text{ (Bq m}^{-2} \text{ s}^{-1}\text{)}} S \delta_N B \frac{D_q}{I_{ih}} \quad (3)$$

where A₀ is the activity of ²²²Rn daughters associated with the release of ²²²Rn (the equilibrium factor

between ^{222}Rn and its daughters is taken to be 0.6); 1.8 Bq m^{-3} is the average outdoor equilibrium equivalent concentration of ^{222}Rn over land and $2 \cdot 10^{-2} \text{ Bq m}^{-2} \text{ s}^{-1}$ is the average emanation rate of ^{222}Rn (see Annex D); as in the previous paragraph, the values of δ_N and B are taken to be equal to 10^{-4} m^{-2} and $2.3 \cdot 10^{-4} \text{ m}^3 \text{ s}^{-1}$, respectively; the values of D_q/I_{th} are derived from Annex D and presented in Table 5.

26. The collective dose commitments due to inhalation during the passage of the cloud, as estimated by the methods described above, are presented in Table 6 for the most important radionuclides discharged into the atmosphere as a consequence of the production of 1 GW a of electrical energy by coal-fired power plants. The corresponding effective dose equivalent commitments are also included in Table 6. The doses due to inhalation of ^{220}Rn and its decay products, estimated in a similar way, are found to be about 1000 times smaller than those from ^{222}Rn and its decay products; they have been neglected here. Finally, the doses from ^{40}K were not calculated because of the homeostatic control by potassium in the body.

27. The collective dose commitments incurred after deposition can be very crudely evaluated by comparison with the natural soil activity concentrations and the corresponding annual absorbed doses in tissues given in Annex B. Assuming that the deposited activity becomes unavailable to the vegetation with a mean life of 100 years for all the natural long-lived radionuclides, and that only the upper 30 cm of soil are involved in the uptake of radionuclides by vegetation, the collective dose commitments per unit energy generated, M_q^c , due to deposition can be assessed as

$$M_q^c = \frac{A_o \dot{D}_q \delta_N \tau}{h C} \quad (4)$$

where A_o is the activity associated with the release of a given radionuclide; \dot{D}_q is the natural dose rate in organ or tissue q due to the radionuclide under consideration; δ_N is the population density; τ is the mean life of the long-lived natural radionuclides in soil taken to be 100 years; h is the thickness of soil involved, expressed as mass per unit area (assumed to be 500 kg m^{-2}); and C is the natural concentration of the nuclide in the soil. In the case of the short-lived radionuclides, especially the isotopes of radon and their daughters, the major contribution to the source term $A_o\tau$ arises from the decay of their long-lived precursors in soil.

28. The collective dose commitments per unit energy generated obtained in this way are presented in Table 7 for external and internal irradiation. It should be noted that the values chosen for \dot{D}_q correspond to the assumption that the contaminated soils and rocks will not be used as components of the building materials. With respect to internal irradiation, the fly-ash particles have been assumed to behave physically and chemically in the same manner as the soil particles, even though the fly-ash particles, being in a vitrified form, are highly insoluble. On the other hand, the doses resulting from direct deposition on vegetation and foodcrops have not been taken into account. The collective effective dose equivalent commitments corresponding to the collective dose commitments presented in Table 7 have also been calculated; they are included in Table 7.

29. The conversion of the collective dose commitments into collective effective dose equivalent commitments allows a better evaluation of the impact of the

various radionuclides and of the various pathways. Table 8 summarizes the collective effective dose equivalent commitments arising from the atmospheric discharges of coal-fired power plants. The production of one gigawatt year of electrical energy is estimated to lead to a total collective effective dose equivalent commitment of 2 man Sv. Inhalation during the cloud passage and internal irradiation due to the activity deposited are found to contribute significantly to the total collective effective dose equivalent commitment. The predominant radionuclides are the isotopes of thorium with regard to inhalation during the cloud passage and ^{210}Pb and the isotopes of radon with respect to internal irradiation due to the activity deposited. Assuming that 70% of the coal produced is used by the power utilities and that the combustion of $3 \cdot 10^9 \text{ kg}$ of coal is necessary to generate 1 GW a, the collective effective dose equivalent commitment resulting from the use of coal in 1979 is estimated to be about 2000 man Sv, on the basis of a world coal production of $3.7 \cdot 10^{12} \text{ kg}$ [U5].

30. The specific activity of ^{14}C in the atmosphere will decrease as a result of the airborne release from coal-fired power plants, thus leading to "negative" collective dose commitments. The Committee has not calculated a numerical value to this effect.

31. Annual individual effective dose equivalents resulting from inhalation during the cloud passage have been estimated. Assuming an effective stack height of 100 m and a uniform wind rose, the annual average of the ground level air concentration per unit release rate experiences a maximum of about $4 \cdot 10^{-8} \text{ Bq m}^{-3}$ per Bq s^{-1} at approximately 1 km from the stack [C6]. On the basis of the activity discharged per unit energy produced given in Table 4 and of the effective dose equivalents per unit activity inhaled presented in Table 5, the annual effective dose equivalent resulting from inhalation during the cloud passage would be about $5 \mu\text{Sv}$ for an individual of the critical group living around a coal-fired power plant producing one GW of electrical power. The annual effective dose equivalents due to ingestion and external irradiation could be of about the same importance [J7].

C. OTHER SOURCES OF RADIATION EXPOSURE RESULTING FROM THE USE OF COAL

32. In the coal fuel cycle, radiation exposures above the natural background are expected to occur mainly when coal has been converted into ash. The production of ash was reported to be 10^7 tons in 1973 in at least four countries: German Democratic Republic, Federal Republic of Germany, Poland and the United States [G11]. Most fly-ash is pumped as a water slurry to settling ponds but some of it, amounting to more than 35% of the production in Belgium, Finland, France and the Federal Republic of Germany [G11], is used in a variety of applications, the largest of which is the manufacture of cement and concrete. Some concretes contain 80% of fly-ash [T2]. Other major uses are as road stabilizers, light-weight aggregates, road fill, and in asphalt mix [M6]. Fly-ash is also used to some extent in agriculture to improve soils [F7, J4]. All those utilizations of ash might lead to increased radiation exposures but very little has been published in this field.

33. Outside of the coal fuel cycle, the combustion of coal for various purposes results in airborne discharges

that have received very little attention. The use of coal for cooking and heating in private homes may lead to high collective dose commitments as the chimneys are low and not equipped with ash removal systems, and as the population densities around the sources of emission are high. Assuming that 5% of the coal produced and that 50% of the resulting ash escapes to the atmosphere means that domestic heating contributes about equally with power production, where 70% of the coal produced releases 2.5% of the ash. The further assumption that the population density around the houses is 10^4 km^{-2} leads to a collective effective dose equivalent commitment due to the world-wide use of coal in 1979 that is very roughly estimated to be of the order of 10^5 man Sv .

II. RADIATION EXPOSURES DUE TO GEOTHERMAL ENERGY PRODUCTION

34. Geothermal energy is produced in Iceland, Italy, Japan, New Zealand, the USSR and the United States. At the present time, it accounts for only 0.1% of the world's energy production [U5] but its relative importance may grow in the future as the potential resources of geothermal energy are believed to be very large. In geothermal energy extraction, use is made of hot steam or water derived from high-temperature rocks deep inside the earth. The geothermal fluids carry natural radionuclides and especially ^{222}Rn , which is discharged into the atmosphere. From measurements of ^{222}Rn activity concentrations in the hot stream used in three Italian power plants, the ^{222}Rn annual releases have been estimated to be 110 TBq from the 400 MW Larderello plant, 7.0 TBq from the 15 MW plant at Piancastagnaio, and 1.5 TBq from the 3 MW plant at Bagnore [M13]. These figures point to an average ^{222}Rn atmospheric discharge per unit energy generated of about 400 TBq per GW a. The corresponding collective effective dose equivalent commitment per unit energy generated is estimated to be about 6 man Sv per GW a if the assumptions used for the discharges from coal-fired power plants are applied. It is recalled that these assumptions are: equilibrium factor of 0.6 between ^{222}Rn and its short-lived decay products; population density of 100 km^{-2} around the plant; effective dose equivalent per unit activity inhaled of $1.3 \cdot 10^{-8} \text{ Sv Bq}^{-1}$; indoor concentrations equal to the outdoor concentrations.

35. Annual individual effective dose equivalents resulting from inhalation of short-lived decay products of ^{222}Rn have also been estimated. Assuming, as in the case of discharges from coal-fired power plants, an effective stack height of 100 m and an annual average of the ground level air concentration per unit release rate of $4 \cdot 10^{-8} \text{ Bq m}^{-3}$ per Bq s^{-1} at 1 km from the stack, the annual effective dose equivalent resulting from atmospheric ^{222}Rn discharges would be about $3 \cdot 10^{-5} \text{ Sv}$ for an individual of the critical group living around a geothermal plant of 1 GW of electrical power. It is to be noted that the existing geothermal plants have a lower power, resulting in correspondingly lower estimates of annual effective dose equivalents.

III. RADIATION EXPOSURES DUE TO THE EXPLOITATION OF PHOSPHATE ROCK

36. Rock phosphate is used extensively, mainly as a source of phosphorus for fertilizers. The world

production of phosphate rock was about $1.3 \cdot 10^{11} \text{ kg}$ in 1977, the main producers being Morocco, the Soviet Union and the United States [U1]. Table 9 presents average activity concentrations of natural radionuclides in phosphate rock from all major phosphate-producing areas of the world. Sedimentary phosphate ores, such as those found in Florida and Morocco, tend to have high concentrations of uranium, whereas magmatic ores, such as apatite from Kola, do not. Typical activity concentrations of ^{238}U are 1500 Bq kg^{-1} in sedimentary phosphate deposits and 70 Bq kg^{-1} in apatite. Uranium-238 is generally found in radioactive equilibrium with its decay products. The activity concentrations of ^{232}Th and of ^{40}K in sedimentary phosphate rock are much lower than those of ^{238}U , and comparable to those observed normally in soil.

37. Mining and processing phosphate ores redistribute ^{238}U and its decay products among the various products, by-products and wastes of the phosphate industry. Effluent discharges into the environment as well as the use of phosphate fertilizers in agriculture and of by-products in the building industry are possible sources of exposure to the public. This section deals mainly with the phosphates of sedimentary origin, as they are the most commonly found and the most likely to lead to enhanced radiation exposures.

A. DOSES ARISING FROM EFFLUENT DISCHARGES

38. Effluent discharges into the environment have been reported for a phosphate rock processing plant and two phosphoric acid production plants [P4], as well as for one uranium recovery plant [D2].

1. Effluents from phosphate rock processing operations

39. The preparation of phosphate rock generally involves strip mining to obtain ore, beneficiation to remove impurities, drying to remove moisture, and grinding to improve reactivity. The major airborne emissions occur in the form of fine rock dust from drying and grinding operations [P4]. The 1976 atmospheric discharges from an ore drying facility in Florida [P4] were about 250 MBq of ^{238}U , in radioactive equilibrium with its decay products down to ^{226}Ra (Table 10). Since that facility processed about $2.7 \cdot 10^9 \text{ kg}$ of wet phosphate rock in the same year, the atmospheric discharges of ^{238}U correspond to approximately 90 Bq per tonne of processed phosphate rock. The atmospheric releases of ^{222}Rn have not been reported; assuming a ^{226}Ra activity concentration in phosphate ore of 1500 Bq kg^{-1} and, conservatively, a 100% release of ^{222}Rn , they would amount to $1.5 \cdot 10^6 \text{ Bq}$ per tonne of processed phosphate rock.

40. During the beneficiation process, marketable rock is separated from sand tailings and clay slimes. These materials are produced in a 1:1:1 ratio. Clay slimes have about the same activity content as marketable rock whereas sand tailings are much less active. Mined-out areas are used in Florida for the disposal of sand tailings and slimes [M4]. Several Florida slime ponds have discharges to the environment. Although no chemical process is used to treat the discharges from the slime ponds, the measured activity concentrations of ^{226}Ra in liquid effluents were all found to be less than 100 Bq m^{-3} . The reduction of total ^{226}Ra from the raw slime to the effluent, primarily due to the removal of

suspended solids by settling, ranged from 92% to greater than 99.9% [M4]. Table 10 presents the ranges in ^{226}Ra activity concentration measured in the dissolved and in the undissolved fraction of the slime and of the effluent in seven mines and beneficiation plants in Florida [G4]. No information appears to be available to the Committee on the actual volume of liquid discharges from those plants.

2. Effluents from phosphoric acid plants

41. Phosphoric acid is produced by two principal methods, the wet process and the thermal process. In the wet process method, usually employed for the production of fertilizers, sulphuric acid is mixed with ground phosphate rock; the subsequent reaction results in the production of phosphoric acid and gypsum: $10 \text{ H}_2 \text{ SO}_4 + \text{Ca}_{10} \text{ F}_2 (\text{PO}_4)_6 + 20 \text{ H}_2\text{O} \rightarrow 10 \text{ Ca SO}_4 \cdot 2 \text{ H}_2\text{O} + 2 \text{ HF} + 6 \text{ H}_3 \text{ PO}_4$. In the reaction, radium is coprecipitated with the gypsum, while uranium and thorium follow the phosphorus into the acid, which is then used to manufacture various fertilizer products. Table 11 presents the estimated distribution of some natural radionuclides among various products of the phosphate industry, in the United States, along with the quantities involved [G5].

42. Apart from gaseous fluorides, which are not radioactive, the airborne effluents of wet phosphoric acid plants consist of dust resulting from the transferring of phosphate rock within the plant. Estimates of the airborne discharges from two wet process phosphoric acid plants located in Florida are given in Table 10 [P4]. The estimated releases, which are based on the measurement of the total particulate emissions and of the total activity concentrations of natural radionuclides in the raw products, are about 100 times higher in plant B than in plant A. However, a stack sampling survey, conducted by the United States Environmental Protection Agency to measure the actual emissions from selected stacks at each facility, showed that the releases from plant B were probably overestimated [P4]. On the basis of information contained in reference [P4] and on the chemical reaction given above, the throughput of marketable ore in plant A and in plant B has been assessed to be about $1.2 \cdot 10^9$ kg. The atmospheric releases of ^{222}Rn have not been reported; assuming a ^{226}Ra activity concentration in phosphate ore of 1500 Bq kg^{-1} and, very conservatively, a 100% ^{222}Rn release, they would amount to $1.5 \cdot 10^6$ Bq per tonne of phosphate ore.

43. Each wet process phosphoric acid plant in Florida incorporates a large cooling pond (about 2 km^2) of contaminated water for recycle in the facility. During periods of excess rainfall, it becomes necessary to discharge water from these ponds to nearby streams [M4]. Raw process water has a pH of 1.5–2.0 and contains $74 \cdot 10^3 \text{ Bq m}^{-3}$ of ^{238}U [G4, M4]. The United States Environmental Protection Agency permits for phosphoric acid plants usually stipulate an acceptable pH range of 6–9 for treated effluent. To accomplish this, slaked lime is normally added. This chemical treatment is highly effective in removing natural radionuclides from the raw process water, as shown in Table 10. No quantitative information on the actual discharges appears to be available to the Committee.

44. In the thermal process normally used for high-grade acid and phosphates, coke and silica are added to

phosphate rock in an electric furnace. The chemical reaction at high temperature produces elemental phosphorus, which is relatively free of radioactivity, and several by-products among which calcium silicate slag, which carries the bulk of the activity initially contained in the phosphate rock, and ferrophosphorus are the most important [B4, G4, M14]. The smelting of the ore results in ^{210}Po and other volatile radioactive material releases [B4]. Actual airborne discharges are not available.

3. Effluents from uranium recovery operations

45. Various processes have been suggested for recovering uranium from phosphate rock [R2, R3]. The plants already existing or being designed for construction in central Florida employ solvent extraction of uranium from phosphoric acid produced at a new process phosphoric acid plant [D2].

46. Annual airborne discharges (Table 10) from a commercial uranium recovery plant in Florida have been estimated to be about 400 MBq of ^{238}U on the basis of limited measurements [D2]. The major contribution to atmospheric radioactive releases was found to occur in the drumming building; the material released was uranium with natural isotopic composition. The production rate of the plant was about 50 tonnes of uranium per year, corresponding to approximately $4 \cdot 10^5$ tonnes of marketable phosphate rock.

4. Environmental concentrations and doses

47. As the heights of atmospheric releases are in general less than 50 m above ground level, surface air measurements in the vicinity of the plants usually show the presence of enhanced concentrations of natural radionuclides.

48. Air activity concentrations of ^{238}U , ^{226}Ra , and ^{230}Th were found to be about $200 \mu\text{Bq m}^{-3}$ at approximately 400 m from the ore drying plant investigated [P4]. In comparison, the average background activity concentrations in the area are about $15 \mu\text{Bq m}^{-3}$.

49. Smaller increases were observed around the two wet process phosphoric acid plants. Average concentrations of about $30 \mu\text{Bq m}^{-3}$ of ^{238}U , ^{226}Ra , and ^{230}Th were measured at approximately 1000 m from the plants [P4].

50. In Idaho, at about 800 m downwind from two adjacent phosphate plants, a wet process plant and a thermal process plant, the annual average gross alpha surface air activity concentration was about $700 \mu\text{Bq m}^{-3}$ in 1974 [B4]. Most of this activity is attributed to ^{210}Po .

51. The main pathways through which the populations living around those plants are exposed to enhanced levels of natural radionuclides are inhalation during the passage of the cloud, and external irradiation, inhalation and ingestion resulting from the activity deposited on the ground. The collective dose commitments corresponding to those pathways have been roughly estimated using the methods already described in paragraphs 24–28 for airborne discharges from coal-fired power plants.

52. The collective dose commitments due to inhalation of all radionuclides except ^{222}Rn and its short-lived decay products are expressed in the form

$$M_q^c = \frac{A_o}{v_d} \delta_N B \frac{D_q}{I_{ih}} \quad (5)$$

where A_o is the annual release (Bq); B is the breathing rate, taken to be equal to $2.3 \cdot 10^{-4} \text{ m}^3 \text{ s}^{-1}$ for an adult; $v_d = 10^{-2} \text{ m s}^{-1}$; δ_N , the human population density, is assumed to be uniform and equal to 100 km^{-2} around the plant; D_q/I_{ih} is the committed absorbed dose in organ or tissue q per unit intake (Gy Bq^{-1}). The values adopted for D_q/I_{ih} are those of Table 5, related to emissions from coal-fired power plants.

53. Regarding inhalation of ^{222}Rn and its short-lived decay products, the expression used is

$$M_q^c = \frac{1.8 (\text{Bq m}^{-3})}{2 \cdot 10^{-2} (\text{Bq m}^{-2} \text{ s}^{-1})} A_o \delta_N B \frac{D_q}{I_{ih}} \quad (6)$$

where A_o is the activity of ^{222}Rn daughters associated with the release of ^{222}Rn (the equilibrium factor between ^{222}Rn and its daughters is taken to be 0.6).

54. The estimated collective dose commitments due to inhalation during the passage of the cloud are presented in Table 12 for some of the radionuclides discharged into the atmosphere as a consequence of processing one tonne of phosphate ore. The radionuclides considered are those for which discharge data have been measured or derived from measurements (see Table 10 and paragraphs 39, 42 and 46).

55. The collective dose commitments incurred after deposition (external irradiation and internal irradiation arising from inhalation of resuspended or emanated material and ingestion of contaminated foodstuffs) can be roughly evaluated by comparison with the natural soil activity concentrations and the corresponding dose rates. As in the case of the airborne discharges from coal-fired power plants (see paragraphs 26 and 27), the expression used is

$$M_q^c = \frac{A_o \dot{D}_q \delta_N \tau}{h C} \quad (7)$$

where A_o is the activity associated with the release of a given radionuclide; \dot{D}_q is the natural dose rate in organ or tissue q due to the radionuclide under consideration; τ is the mean life of the long-lived natural radionuclides in soil, taken to be 100 years; h is the thickness of soil involved, expressed as mass per unit area (assumed to be 500 kg m^{-2}); and C is the natural concentration of the nuclide in the soil. The collective dose commitments per unit mass of marketable ore processed obtained in this way are presented in Table 13.

B. DOSES ARISING FROM THE USE OF PHOSPHATE FERTILIZERS

56. The world production of phosphate fertilizers was approximately $3 \cdot 10^{10} \text{ kg}$ of P_2O_5 in 1977 [U1]. Assuming that the activity distribution given in Table 11 holds on a global basis, the mass of marketable rock necessary to produce such an amount of phosphate fertilizers was about 10^{11} kg , which is approximately three-quarters of the world production of marketable ore in that year ($1.3 \cdot 10^{11} \text{ kg}$).

57. The application rate of fertilizers depends inter alia on the type of soil and on the type of crop. The average consumption of phosphate fertilizer per hectare of agricultural land varied in 1977 from $0.9 \text{ kg P}_2\text{O}_5$ for the African continent to $37.6 \text{ kg P}_2\text{O}_5$ for Europe, the world average being $6.3 \text{ kg P}_2\text{O}_5$ [F3]. The amounts of fertilizer applied annually by crop in the United States have been reported to range from about $30 \text{ kg P}_2\text{O}_5$ per hectare for barley, wheat and oats to about $150 \text{ kg P}_2\text{O}_5$ per hectare for potatoes and tobacco [N4].

58. Measured activity concentrations of naturally-occurring radionuclides in phosphate fertilizers from several countries are summarized in Table 14. With the exception of basic slag (a by-product of the manufacture of steel), all the fertilizers considered in Table 14 are derived from phosphate ore processing. For a given radionuclide and type of fertilizer, the concentrations vary markedly from one country to the other, depending on the origin of the components. Relatively high concentrations of ^{238}U are observed or should be expected when the phosphate ore is of sedimentary origin, while low concentrations are associated with ore of magmatic origin.

59. The degree of radioactive equilibrium between ^{238}U and its decay products depends on the type of manufacturing process used and more specifically on the relative contribution of phosphoric acid in the end-product, since phosphoric acid has usually a very low content of ^{226}Ra . The lack of equilibrium between ^{238}U and ^{226}Ra is particularly clear for triple superphosphates and ammonium phosphates. Other general features that can be observed in Table 14 are that the concentrations of ^{232}Th are always low; with the exception of the potassium fertilizers, the concentrations of potassium (and thus ^{40}K) are also generally low; that the concentrations of ^{226}Ra do not exceed 1000 Bq kg^{-1} ; and that ^{210}Pb and ^{210}Po are generally close to radioactive equilibrium with ^{226}Ra .

60. Phosphate fertilizers contribute to the external radiation exposure of persons occupationally handling phosphates and of members of the public. Through the contamination of foodstuffs, they also contribute to internal irradiation of mankind.

61. Pfister and Pauly [P7] have estimated the external radiation exposure of members of the public and of the small group of persons working in production, transport, storage and application of rock phosphates and phosphate fertilizers in the Federal Republic of Germany. With regard to the dispersal of phosphate fertilizers in agricultural areas, they assessed the average addition to the soil activity in 1977–1978 at 17 Bq m^{-2} of ^{238}U , 11 Bq m^{-2} of ^{226}Ra , 7.4 Bq m^{-2} of ^{232}Th and 150 Bq m^{-2} of ^{40}K . Assuming an accumulation of ^{226}Ra in the soil during the last 80 years, a mean additional absorbed dose rate in air of about $8 \cdot 10^{-4} \mu\text{Gy h}^{-1}$ was calculated. Fertilizer application therefore results in a fairly small increase of the external radiation exposure over natural background which, on average, is $0.05 \mu\text{Gy h}^{-1}$ (see Annex B). In contrast, the occupational radiation exposure of individuals can be much higher. Pfister and Pauly [P7] measured mean additional absorbed dose rates in air ranging from 0.02 to $0.23 \mu\text{Gy h}^{-1}$ for various transport and loading operations and peak values of $0.8 \mu\text{Gy h}^{-1}$. In agricultural storehouses, they measured a mean additional absorbed dose rate in air of $0.09 \mu\text{Gy h}^{-1}$. It is possible, however, that inhalation of fertilizer dust might lead to higher doses.

62. A slight increase in the concentrations of natural radionuclides of the ^{238}U series is also expected to occur in food crops grown on soils supplied with high amounts of phosphate fertilizers. Kirchmann et al. [K5] measured the ^{226}Ra activity concentration in straw and grain of wheat harvested in plots fertilized for 11 years with controlled amounts of phosphate fertilizers. There was no significant difference in the ^{226}Ra concentrations of wheat harvested in the plots fertilized at high levels (1356 kg P_2O_5 per hectare) or at low levels (343 kg P_2O_5 per hectare). However, the ^{226}Ra soil contamination resulting from the application of phosphate fertilizers represented respectively only 1.08% and 0.25% of ^{226}Ra activity of natural origin observed in the upper layer of soil [K5]. The small relative contribution of the ^{226}Ra content in the fertilizer to the natural ^{226}Ra content in the soil, combined with the fact that the fertilizer was homogeneously mixed in the soil, is likely to have precluded experimental evidence of an increased ^{226}Ra concentration in wheat. Other tests with fertilizers labelled with ^{226}Ra have shown that the radionuclide uptake by plants is practically the same whether it is included in fertilizer or in soil structures [D5].

63. However, foodstuffs may be contaminated to a greater extent if, for example, fertilizers are applied in liquid form on the soil surface or if phosphate products are used to feed animals. Phosphate products are extensively used as a source of phosphorus in livestock feed supplements. Activity concentrations of ^{226}Ra in livestock feed supplements have been measured in the United States to range from 7 to 1600 Bq kg^{-1} [R5], which is consistent with the values presented in Table 14 for phosphate fertilizers. An assessment of the transfer to milk of ^{226}Ra ingested by dairy cows in their feed supplements showed that the maximum ^{226}Ra concentration in milk would be about 25 Bq m^{-3} , to be compared with "normal" concentrations of 3 to 10 Bq m^{-3} [R5].

64. The collective dose commitments arising from the decision to use one tonne of marketable ore to produce phosphate fertilizer can be crudely estimated with the method used in paragraph 55. According to the data presented in Table 11, one tonne of marketable rock produces 0.54 tonne of fertilizer. On the basis of the results presented in Table 14, the average activity concentrations of natural radionuclides in phosphate fertilizers are taken to be 600 Bq kg^{-1} for ^{238}U , ^{234}U and ^{230}Th , and 400 Bq kg^{-1} for ^{226}Ra and for each of its decay products. Therefore, one tonne of marketable ore is estimated to produce 0.54 tonne of phosphate fertilizers containing about 3×10^5 Bq of ^{238}U and 2×10^5 Bq of ^{226}Ra and of each of its decay products. The activity concentrations of ^{40}K and of the radionuclides of the ^{232}Th series are generally low and the corresponding doses have been neglected.

65. Assuming that the ploughed layer of soil is 30 cm deep; the availability to plants of natural radionuclides is the same whether in fertilizer or in the normal constituents of the soil; the deposited activity becomes unavailable to the vegetation with a mean life of 100 years for the long-lived natural radionuclides; and the fraction of time spent by the populations exposed on, or near, fertilized fields is 1%; then the collective dose commitments per unit mass of marketable rock arising from external irradiation and from internal irradiation (resuspension and emanation from soil and ingestion of contaminated foodstuffs) may be calculated as in Table 15.

C. DOSES ARISING FROM THE USE OF BY-PRODUCTS AND WASTES

66. The main by-products resulting from processing phosphate ore in phosphoric acid plants are gypsum (or phosphogypsum) in wet process plants and calcium silicate slag in the thermal process plants. Radiation exposure to members of the public can occur if those by-products are used in the building industry. Another source of exposure stems from the reclamation of land on which phosphate mining has been completed and houses have been allowed to be built.

67. Large quantities of phosphogypsum are produced in the wet process phosphoric acid plants. The annual world production of phosphogypsum was approximately 9×10^{10} kg in 1974, which is greater than the production of natural gypsum [F4]. As shown in Table 11, the mass of phosphogypsum produced is about the same as that of the phosphate ore processed and the bulk of the ^{226}Ra content of the phosphate ore is transferred to phosphogypsum. The average activity concentration of ^{226}Ra in phosphogypsum was taken to be about 900 Bq kg^{-1} in Annex B of the 1977 report [U2].

68. Phosphogypsum can replace natural gypsum in the building industry and thus be used to make blocks and plaster board, partition systems and also cement [N5, O2, O3]. The practice of using this waste product has been considered attractive, since overall building costs are reduced, natural resources are preserved, and environmental pollution is decreased. On the other hand, since phosphogypsum contains a much higher concentration of ^{226}Ra than its natural counterpart, its use increases the radiation doses to the public.

69. Japan was the first country to employ phosphogypsum for construction purposes in 1934 [S4]. In 1974, approximately 3×10^9 kg of phosphogypsum was used in Japan in the construction industry, half of it as setting controller for cement. The use of phosphogypsum for plaster, plasterboard and building blocks has gained importance throughout the world [S4].

70. O'Riordan et al. [U2] estimated the additional doses that would be received by the occupants of a residential building in which 4.2 tonnes of by-product gypsum (considered to be a high, but realistic amount) would have replaced the established materials. Assuming the ^{226}Ra concentration of phosphogypsum to be 900 Bq kg^{-1} , they estimated the additional absorbed dose rate in air to be 0.07 $\mu\text{Gy h}^{-1}$, and the additional radon concentration, using a ventilation rate of 1 h^{-1} , to be about 10 Bq m^{-3} .

71. If it is assumed that all the phosphogypsum produced by 1 tonne of marketable ore is used in the building industry, that on the average four persons live in the dwellings so constructed, and that the mean life of the dwelling is 50 a, the whole-body collective dose commitments due to external irradiation can be evaluated from the estimates provided by O'Riordan et al. [O2], to be about 0.02 man Gy t^{-1} . Assuming that the equilibrium factor between radon and its short-lived decay products is 0.6, the collective effective dose equivalent commitments arising from indoor inhalation would also be about 0.02 man Sv t^{-1} .

72. It should be indicated that phosphogypsum is also used in agriculture as an amendment to improve water movement in saline-alkaline soils and may also be substituted for limestone or lime to supply calcium to

alkaline soils [L3]. Owing to the low solubility of RaSO_4 and to the effect of the presence of calcium, the ^{226}Ra soil-plant transfer coefficient for plants grown on phosphogypsum-treated soils should be smaller than under "normal" conditions [L3].

73. Calcium silicate slag is a by-product of phosphate ore processing by the thermal process. With the exception of ^{210}Po , which is driven off during smelting, the measured concentrations of the natural radionuclides of the ^{238}U series were found to be about the same in the phosphate ore and in the slag [B4, G4, P5].

74. In Idaho, about 2.4×10^9 kg of slag are produced each year [B4]. Measured activity concentrations in slag samples are 1300–1500 Bq kg^{-1} of ^{226}Ra , 740 Bq kg^{-1} of ^{230}Th and 1000 Bq kg^{-1} of ^{238}U . About one-tenth of this product is sold to slag crushing operations that market the material for railroad ballast, asphalt, concrete, and other uses. In that way, about 800 GBq of ^{226}Ra was distributed into the environment in the areas of Pocatello and Soda Springs in 1974. The number of structures and dwellings constructed with slag in concrete is estimated to be approximately 150. Gamma surveys were conducted in Soda Springs and Pocatello. Above asphalt containing slag, the average external gamma absorbed dose rate in air was found to be about $0.08 \mu\text{Gy h}^{-1}$ above background, the maximum level being approximately $0.3 \mu\text{Gy h}^{-1}$. The preliminary results from the indoor survey indicate that the gamma absorbed dose rate in air can also be as high as $0.3 \mu\text{Gy h}^{-1}$ above background in dwellings constructed with 43% by weight slags in concrete slabs [B4]. In comparison, the average gamma absorbed dose rate in air received indoors is estimated as $0.06 \mu\text{Gy h}^{-1}$ in Annex B.

75. In Canada, about 21 000 tonnes of slag arising from a thermal process plant using Florida phosphate rock as input feed has been crushed and used in roadbeds, laneways, backfill around basements, and as a base for concrete floors in basements of dwellings [M14]. Measurements of slag samples indicated a ^{226}Ra activity concentration of 2150Bq kg^{-1} . A gamma survey was conducted inside homes with slag and without slag. For 24 dwellings with slag, the average absorbed dose rate in air was $0.12 \mu\text{Gy h}^{-1}$ with a standard deviation of $0.04 \mu\text{Gy h}^{-1}$. The range of values observed was 0.07 to $0.21 \mu\text{Gy h}^{-1}$ (excluding two houses in which crushed slag had been spread over the basement excavation to form an unfinished floor, resulting in measured absorbed dose rates in air of 0.33 and $0.54 \mu\text{Gy h}^{-1}$, respectively). By comparison, the average absorbed dose rate in air for 54 homes without slag was $0.09 \mu\text{Gy h}^{-1}$, with a standard deviation of $0.02 \mu\text{Gy h}^{-1}$ and a range of 0.05 to $1.5 \mu\text{Gy h}^{-1}$. Thus the use of slag has led to an apparent increase of $0.033 \mu\text{Gy h}^{-1}$. This difference is, however, not statistically significant because of the standard deviations given above [M14].

76. A similar situation has been discovered to occur in Florida [A2]. Approximately 250 000 tonnes of slag are used each year for paving roads, as ballast, as material for railroad beds, and for house roofing material. An investigation was conducted by the United States Environmental Protection Agency [A2].

77. Residents in structures built on "reclaimed" Florida phosphate land may also be exposed to enhanced radiation doses. About 600km^2 of Florida land have been mined for phosphate rock in the last 80 years. Of that amount, about 200km^2 have been

reclaimed to various degrees. It is estimated that 4000 structures may be built on phosphate lands in central Florida [R6]. Absorbed dose rates in air were measured in and out of 672 structures built on reclaimed land. The average absorbed dose rate in air was found to be $0.092 \mu\text{Gy h}^{-1}$ outdoors, the highest one $0.35 \mu\text{Gy h}^{-1}$ [G7, G8]. By comparison, the natural background outside the phosphate area is approximately $0.05 \mu\text{Gy h}^{-1}$. The indoor levels reflected the degree of floor shielding present in the various structure categories. Absorbed dose rates in air in excess of $0.17 \mu\text{Gy h}^{-1}$ were only observed in crawl space and trailer constructions, which have either wood or thin metal flooring [G7]. The equilibrium equivalent radon concentration in houses ranged from 4 to 500Bq m^{-3} with a weighted average of about 40Bq m^{-3} which is estimated to be 26Bq m^{-3} above normal concentrations in houses of that area. This average additional concentration results in an annual effective dose equivalent of approximately 1.6mSv .

D. RECAPITULATION

78. Table 16 summarizes the radiation exposures due to the exploitation of phosphate rock, expressed in terms of collective effective dose equivalent commitments resulting from the decision of using a unit mass of marketable ore to accomplish a defined purpose. The most important natural radionuclides have been taken into account.

79. The impact from one year of phosphate ore processing has been very crudely estimated on the basis of the following data and assumptions:

- (a) The world production of marketable rock is 1.3×10^{11} kg in a typical year;
- (b) All the marketable ore is processed in ore drying plants;
- (c) Seventy per cent of the marketable ore production is used to prepare phosphate fertilizers;
- (d) With regard to the wet process phosphoric acid plant, the results relative to plant A (see Tables 12 and 13, and paragraph 42) are adopted;
- (e) Ten per cent of the by-product gypsum is used as building material in dwellings.

80. On the basis of these assumptions, the collective effective dose equivalent commitment resulting from the 1977 production of phosphate rock is estimated to be about 3×10^5 man Sv; by far, the most important contribution to the total dose is due to the use of by-product gypsum in dwellings. The total of the other contributions to the collective effective dose equivalent commitment is only about 6000 man Sv.

IV. ENHANCED INDOOR EXPOSURES

81. Indoor exposures result mainly from external irradiation and from inhalation of radon decay products. The general aspects of indoor exposures are discussed in Annexes B and D. This section deals essentially with elevated indoor exposures. High external irradiation rates usually arise from high concentrations of natural radionuclides (especially ^{226}Ra) in building materials and in soil. Elevated concentrations of radon decay products may be due to the same reasons or to high radon influx from the soil, or to high radon concentrations in water or natural gas used in homes.

82. *Building materials.* As exemplified in Table 17, the use of some building materials may lead to elevated indoor radiation levels. The building materials may be of natural origin, such as pumice stone (Federal Republic of Germany and the USSR), concrete containing alum shale (Sweden), lithoid tuff (Italy), and granite wherever it is used. They may also result from industrial processes. In the non-uranium industries, the use of phosphogypsum and of calcium silicate slag, two by-products of the phosphate industry have already been discussed. Other by-products that were shown to contain relatively high concentrations of naturally-occurring radionuclides were red mud, a waste product of aluminium mills, and blast furnace slag, a by-product of iron manufacture [K7].

83. In its basic radiation standards, the National Commission of Radiation Protection of the USSR [K8] used a dosimetric relationship. If the concentrations of ^{40}K , ^{226}Ra and ^{232}Th , expressed in Bq kg^{-1} , in materials made of industrial wastes satisfy the expression

$$\frac{C(^{40}\text{K})}{4810} + \frac{C(^{226}\text{Ra})}{370} + \frac{C(^{232}\text{Th})}{259} \leq 1 \quad (8)$$

it was estimated that the increase over background of the gonad absorbed dose indoors from external irradiation is less than 1.5 mGy in a year. In comparison, the average absorbed dose in all tissues received indoors from external irradiation of terrestrial origin is assessed as 0.3 mGy in a year in Annex B. The measurements of activity concentrations of naturally-occurring radionuclides in building materials in the Soviet Union [K8] showed that only a few materials would not satisfy the expression given above, while in the Federal Republic of Germany it was found that 12% of the analysed samples would exceed that limit [K7].

84. It should be pointed out that the average absorbed dose rates in air measured in buildings using these materials are much lower than what would be expected from the radioactive content of the materials considered, because materials usually less active are also used in the same buildings. For example, the average absorbed dose rate derived from measurements carried out in Swedish houses made of aerated concrete containing alum shale is about $0.17 \mu\text{Gy h}^{-1}$ [M7], while the value given in Table 17, calculated from the activity concentration of radionuclides in that type of concrete, using very pessimistic assumptions, is $1.5 \mu\text{Gy h}^{-1}$ [S6]. Measurements of radon daughters have been carried out in 32 single-family houses containing a large fraction of concrete based on alum shale in their building materials [S13]. The average equilibrium equivalent concentration of radon in those houses was found to be 260 Bq m^{-3} , corresponding to annual effective dose equivalents of 16 mSv.

85. Waste products of the uranium and radium industry have been used as building materials. In the United States, notably in Grand Junction, Colorado, tailings from uranium mills were used during the period 1952–1966 as fill material under houses and as building materials [U4]. Remedial action was deemed necessary by the national authorities more because of the elevated radon concentrations measured in houses than because of the external radiation doses. The average equilibrium equivalent concentration of radon measured in 47 houses was about 200 Bq m^{-3} [C7]. It is in many cases true that when building materials containing high concentrations of ^{226}Ra are used in dwellings, the occupants receive a higher effective dose equivalent

rate from inhalation of ^{222}Rn and its short-lived decay products than from external irradiation.

86. In the town of Port Hope, Ontario, Canada, another type of problem arose from a plant which had recovered radium in the 1930s and the 1940s from pitchblend-radium-silver ores [S7]. In this particular case, the potential radon problem was not recognized and consequently much contaminated construction and fill material was used in and around the houses in the town. As in the case of Grand Junction, remedial action was deemed necessary by the national authorities.

87. *Radium in soil.* In Sweden, areas containing tailings from the alum shale industry have been built on. The radium concentration of the tailings is on average 2900 Bq kg^{-1} and the outdoor gamma radiation dose rate in air is of the order of $1 \mu\text{Gy h}^{-1}$ [S14]. In houses, the equilibrium equivalent concentration of radon was found to be 500 Bq m^{-3} on average [S14], corresponding to annual effective dose equivalents of about 30 mSv. In March Township, Ontario, Canada, 343 houses were surveyed because of the discovery of nearby low-grade uranium deposits. The highest equilibrium equivalent concentration of radon was 700 Bq m^{-3} and the weighted arithmetic average 50 Bq m^{-3} [L5]. This weighted average is estimated to result in annual effective dose equivalents of 3 mSv received indoors.

88. *High radon influx from soil.* In the Chicago area, United States, high radon concentrations have been found in houses with unpaved crawl spaces while the radium concentration in soil was normal [R9]. In a total of 22 houses investigated, the radon concentration was more than 185 Bq m^{-3} in nine houses and more than 370 Bq m^{-3} in six of these. Most of the radon emanated from the unpaved crawl space under the house. In Sweden, it is estimated that about 75% of the total collective dose caused by inhalation of radon daughters arises from radon emanating from the ground. Houses have been found with more than $10\,000 \text{ Bq m}^{-3}$ of radon. An equilibrium equivalent concentration of radon of $10\,000 \text{ Bq m}^{-3}$ is estimated to yield an annual effective dose equivalent of about 600 mSv received indoors.

89. *Radon in water.* Radon in water may be a significant source of radon in the air in dwellings in many countries. In the region of Helsinki, Finland, very high concentrations of radon in water from deep wells, ranging up to 44 MBq m^{-3} , have been reported [C8]. From measurements of air concentration of radon in 20 houses [A5], it can be derived that the average equilibrium equivalent concentration of radon would be 360 Bq m^{-3} with a maximum value of 1200 Bq m^{-3} . In Canada, the area of Castlegar-Trail in British Columbia, was surveyed because of high radon concentrations in water. The weighted average equilibrium equivalent concentration of radon in indoor air was found to be about 70 Bq m^{-3} while the highest value was 2900 Bq m^{-3} [L5].

90. *Radon in gas.* Natural gas containing radon may also be a significant source of radon in indoor air if it is used in unvented appliances. Average radon concentration in natural gas in various distribution lines have been reported to be within the range of 40 to 2000 Bq m^{-3} [J9, W9]. Assuming that natural gas is used in unvented kitchen ranges, the resulting additional indoor air concentrations are estimated to be only about 0.01 to 0.3 Bq m^{-3} .

91. In conclusion, enhanced indoor exposures may be due to various reasons and may give rise to high individual doses. More detailed information on the elevated indoor concentrations of radon that have been measured in several countries is provided in Annex D. The collective doses have not been quantified owing to the lack of data on the number of houses involved. Further measurements are required in that field.

V. ENHANCED EXPOSURES TO COSMIC RAYS

A. PASSENGERS IN AIRCRAFT

92. The number of passenger kilometres flown throughout the world in scheduled commercial flights was 9.34×10^{11} in 1978 [12]. Taking the average speed to be 600 km h^{-1} , a total of about 1.6×10^9 passenger hours was spent travelling in that year. The dose rates incurred during the flights vary according to the altitude and, to a smaller extent, to the latitude and to the solar activity. Table 18 shows the variation with altitude, from 4 to 20 km, of the dose rate and of the dose equivalent rate averaged over two geomagnetic latitudes and two periods of solar activity [O4]. The altitudes of subsonic flights depend on the type of aircraft used and on the distances covered in a given flight. They could be as low as 2–3 km for short flights and as high as 12 km for intercontinental flights, with intermediate values of 5–10 km for medium-range and continental flights [H2, W1, W2]. Table 18 shows that the dose rate and the dose equivalent rate vary by a factor of 20 between the altitudes of 4 and 12 km. Assuming that the average altitude of commercial flights is 8 km, the average dose rate would be $0.84 \mu\text{Gy h}^{-1}$ and the average dose equivalent rate $1.35 \mu\text{Sv h}^{-1}$, yielding a collective effective dose equivalent to the world population of about 2000 man Sv from air transportation in 1978.

93. Supersonic aircraft (SST), which are used on a small scale, fly at altitudes ranging up to 20 km, compared with at most 12 km for standard jet aircraft. Assuming that SSTs fly at an average altitude of 16 km, the average absorbed dose rate would be about $6 \mu\text{Gy h}^{-1}$ (Table 18). Actually, the absorbed dose rates measured on board the commercial SST flights of Air France, averaged over the years 1976–1980, amount to about $5 \mu\text{Gy h}^{-1}$ [P8]. Taking from Table 18 the quotient of the dose equivalent to the absorbed dose to be 1.6 Sv Gy^{-1} , the corresponding dose equivalent rate is about $8 \mu\text{Sv h}^{-1}$.

94. Wallace [W2] calculated absorbed doses to passengers for a round trip, for both subsonic and supersonic transport between various city pairs. Some of these estimates are shown in Table 19. Doses for a round trip in supersonic aircraft are approximately 70% of those for subsonic speeds, because of the shorter flying time. However, the dose rates in supersonic aircraft are about twice as high as in subsonic aircraft. For a round trip across the Atlantic, the tissue absorbed doses in passengers may be estimated to be about $2 \times 10^{-5} \text{ Gy}$ for an SST and $3 \times 10^{-5} \text{ Gy}$ for a subsonic aircraft, under average solar conditions.

95. All the dose values given above refer to galactic cosmic rays. There is, in addition, a contribution due to the solar flares. From dose rate values given in the 1972 UNSCEAR report [U6], based on results obtained by

an ICRP working group by averaging the effects of solar flares over the period 1952–1960 [13], the average absorbed dose index rates from solar radiation can be estimated to be $4 \times 10^{-8} \text{ Gy h}^{-1}$ at 12 km and $9 \times 10^{-7} \text{ Gy h}^{-1}$ at 20 km. The average contribution from this source is thus small compared with that from galactic cosmic rays.

96. Although radiation of solar origin does not contribute significantly to the average absorbed dose index rate, during an occasional intense solar flare radiation levels at these altitudes may increase by several orders of magnitude. The giant solar flare events last only for about 10 h and occur a few times in each solar cycle, and therefore are not likely to add significantly to the collective dose of the world population. It is worth mentioning that SST aircraft carry radiation monitors, and the pilots will move the aircraft to lower altitudes when the dose rate reaches a prescribed level.

B. ASTRONAUTS

97. When travelling into space, astronauts are subjected to primary cosmic ray particles, the radiation from solar flares, and also the intense radiation present in the two radiation belts. Savun et al. [S8] have reported measurements in the radiation belts in 1971. Measurements inside a 0.7 g cm^{-2} shield indicate that the maximum absorbed dose rate crossing the inner belt was 0.22 Gy h^{-1} and crossing the outer belt 0.054 Gy h^{-1} .

98. Estimated absorbed doses received by astronauts on several Apollo missions (average for the three occupants) based upon measurements carried out with tissue-equivalent ionization chambers are shown in Table 20 [C3, E2, R7, G9]. A large part of this dose was received while the spacecraft was passing through the earth's radiation belts. For example, the higher dose received on the Apollo X mission was largely due to a different trajectory through the radiation belts. Analogous data in Table 20 from space flights of the USSR (Vostok, Voskhod and Soyuz series) indicate doses of comparable magnitude [G9]. Table 21 indicates the breakdown of the absorbed dose and of the dose equivalent on the first lunar landing mission, Apollo XI [E2].

99. In outer space, remote from the shielding influence of the earth's magnetic field, the absorbed dose index rate from solar protons emitted during solar flares can be very high. For example, it has been estimated that the absorbed dose indices in outer space from the solar proton event of 10 July 1959 were: from protons 3.6, 1.7, and 0.4 Gy behind shielding of 1.2 and 5 g cm^{-2} , respectively, and from alpha particles the corresponding values were 1.5, 0.3 and 0.05 Gy , respectively [C3]. However, the Apollo missions did not experience any measurable solar particle events [E2].

VI. MISCELLANEOUS SOURCES OF RADIATION

100. In the present context the term miscellaneous sources indicates a variety of radiation sources which the general public is exposed to during the normal course of its activities, generally without being aware of them. Those sources of radiation result from man-made

activities. Most of them are consumer products containing radioactive substances that have been deliberately incorporated to satisfy a specific purpose.

A. CONSUMER PRODUCTS

101. The consumer products containing deliberately incorporated radionuclides can be broadly classified into five categories: radioluminous products; electronic and electrical devices; antistatic devices; smoke detectors; and ceramic, glassware, alloys, etc. containing uranium or thorium. Some of these products, such as the antistatic devices, are more widely disseminated in industry than among the general public.

102. Table 22 presents some information on the number of products and the activities involved in each category in the Federal Republic of Germany [W3]. Although the data shown are not contemporaneous as some correspond to the year 1973 and others to the year 1975, the table gives a good idea of the relative importance of each category in an industrialized country.

1. Radioluminous products

103. Radium-226, promethium-147, and tritium have been used extensively in the dial-painting industry for the illumination of timepieces, the radiation emitted by those radionuclides being converted into light by a scintillator, which is usually zinc sulphide containing small amounts of copper or silver. From the public health point of view, one of the major disadvantages of radium is its inherent emission of a great deal of penetrating radiation which is not useful for the production of light yet irradiates the whole body of the watch wearer. Radium tends to be replaced by ^3H and ^{147}Pm , which are soft beta emitters and thus cause much smaller external radiation doses to the watch users.

104. Table 23 presents estimates of the numbers of radioluminous watches and clocks in use in Switzerland, the United Kingdom and the United States. The values for the United States are based on production data assuming that the average useful life of a luminous timepiece is 3 years [M8]. The estimates from Switzerland are an extrapolation to the whole population of the country of the results of a survey involving 1032 consumers [K9]. The data for the United Kingdom are based on information from the watch trade [T1]. It is clear from the table that most of the radioluminous watches contain tritium; in clocks, ^{147}Pm and ^{226}Ra seem to be more used than ^3H .

105. The activities of ^3H and ^{147}Pm which produce the same brightness as 37 kBq of ^{226}Ra have been estimated to be about 200 TBq of ^3H and 6 TBq of ^{147}Pm for a newly manufactured timepiece [14]. However, owing to radioactive decay, release of activity and deterioration of the phosphor, the brightness decreases continuously over the useful life of the timepiece at a rate that depends upon the radionuclide used. The activities of ^3H and ^{147}Pm required to produce the same average brightness as 37 kBq of ^{226}Ra over the useful life of the timepiece, taken to be three years, have been estimated to be about 300 TBq of ^3H and 10 TBq of ^{147}Pm [M9].

(a) Absorbed doses from ^{226}Ra -activated timepieces

106. The absorbed doses from ^{226}Ra -activated timepieces result mainly from external irradiation, the release of radon being usually insignificant. As indicated in Annex B of the 1977 report [U2], an annual gonad dose per unit activity of $1.6 \cdot 10^{-8}$ Gy Bq $^{-1}$ is estimated for wrist-watches worn continuously. According to the recommendations issued by a joint group of experts from OECD and IAEA [14], the total activity of ^{226}Ra should be limited to 3.7 kBq. That limit corresponds to a gonad absorbed dose in a year of 40 μGy if the watch is worn on average 16 hours per day. However, as the production of ^{226}Ra -luminous watches has stopped in many countries, a significant fraction of the existing ^{226}Ra -painted watches is likely to have been manufactured in the 1950s or the early 1960s, and to contain greater activities than the limit.

107. The external radiation gonad dose per unit activity to the user of an alarm clock has been calculated for an exposure of 8 h per day at a distance of 2 m to be $1.6 \cdot 10^{-10}$ Gy Bq $^{-1}$ [M8]. Assuming that the ^{226}Ra activity contained in the alarm clock is 5.5 kBq, which is the limit recommended [14], the annual gonad dose would be about 1 μGy ; the annual effective dose equivalent would be about 1 μSv .

(b) Absorbed doses from ^3H -activated timepieces

108. As shown in Table 22, most of the radioluminous watches currently in use are luminized with tritium paint. The external dose from a tritium luminous watch is negligible because of the low energy of the β -particles and of the bremsstrahlung arising from the decay of ^3H . However, tritiated water or tritiated organic molecules evolve slowly from the tritium paints leading to internal absorbed doses to wearers from inhalation and skin absorption.

109. The relationship between the ^3H activity in watches and the resulting whole-body absorbed dose has been studied under controlled conditions by Moghissi and Carter [M9]. The average dose in a year per unit activity of tritium paint, from a watch worn continuously, was found to be $8 \cdot 10^{-15}$ Gy Bq $^{-1}$, the range being $3 \cdot 10^{-15}$ to $1.2 \cdot 10^{-14}$ Gy Bq $^{-1}$.

110. There are as yet no published estimates of doses from ^3H -activated alarm clocks. The activity-to-dose relationship has been conservatively assumed to be the same as that adopted for watches. Taking into account the fact that the exposure occurs only 8 hours per day on average, the quotient of annual dose to activity would be about $3 \cdot 10^{-15}$ Gy Bq $^{-1}$ for alarm clocks.

111. The average content of tritium in luminous timepieces has been determined in Switzerland to be 37 MBq for wrist-watches and 60 MBq for clocks [K9]. In the United States, the records from the Nuclear Regulatory Commission suggest an average of 25 MBq for watches and 15 MBq for clocks [M8]. In this Annex, a single value of 40 MBq will be adopted for the purpose of dose calculations. It results in a whole-body dose of 0.3 μGy for the wearer of a tritium-painted watch, and of 0.1 μGy for the user of a tritium-painted clock. The corresponding annual effective dose equivalents would be 0.3 μSv and 0.1 μSv , respectively.

112. With the advent of liquid-crystal displays, the use of gaseous tritium light sources (GTLS) to illuminate

digital watches could become widespread in the near future. A GTLS consists of a hollow glass tube whose inside walls are coated with an inorganic phosphor. The tube is evacuated, back-filled with tritium gas, and laser sealed. For watch applications, the tritium content is much higher than in a painted watch; it was observed to range from 1.7 GBq to 7.4 GBq [W4]. A total of approximately 40 000 timepieces were distributed during 1976 in the United States [R8]. Preliminary tests indicate that the dose to the wearer will result from tritium permeating through the glass and being absorbed into the body [W4]. It appears at present that on average the dose to the wearer of a watch luminized with a GTLS containing 7.4 GBq of ^3H may be of the same order as that to the wearer of a typical watch luminized with ^3H paint [T1]. There will also be internal dose to a person breaking the source which is usually sealed in a metal or glass capsule with the liquid-crystal display and is not easily accessible to the wearer. Out of the 40 000 timepieces distributed in 1976 in the United States, two watches were returned for tritium tube breakage [R8]; thus only a small fraction of the tritium is returned to the environment.

(c) *Absorbed doses from ^{147}Pm -activated timepieces*

113. Since promethium is a solid, it does not evolve from a watch under normal conditions of usage, so that the risk of external radiation is the only one that has to be considered. Promethium-147 is a pure beta emitter. The maximum energy of its beta particles is 224 keV, corresponding to a range of 46 mg cm^{-2} . Since the standards set by the OECD and the IAEA recommend a minimum thickness of 50 mg cm^{-2} for the casing of timepieces, no exposure hazard from beta radiation should exist. However, a low external radiation dose from bremsstrahlung has to be expected. Moghissi and Carter [M9] have conservatively estimated the annual gonad dose per unit activity to be $1.4 \cdot 10^{-12}$ Gy Bq^{-1} . The average ^{147}Pm content of timepieces is suggested to be 1.5 MBq on the basis of a search of the records of the United States Nuclear Regulatory Commission. The resulting gonad dose to the wearer of a ^{147}Pm -painted watch would be approximately 2 μGy and the annual effective dose equivalent would be about 2 μSv .

114. There are no published estimates of doses from ^{147}Pm -activated clocks. In the case of ^{226}Ra , the ratio of the gonad doses from a watch and from a clock is 100; the same ratio will be assumed for ^{147}Pm , although it is recognized that the energies of the electromagnetic radiation involved are much lower for ^{147}Pm than for ^{226}Ra . The gonad dose in a year to the user of a ^{147}Pm -painted alarm clock would therefore be approximately 0.02 μGy and the effective dose equivalent would be about 0.02 μSv .

(d) *Collective doses from radioluminous timepieces*

115. The annual collective effective dose equivalents arising from the use of radioluminous timepieces have been estimated, for the populations of Switzerland, the United Kingdom, and the United States, on the basis of the number of products presented in Table 23, of the activity contents per type of product and of the quotients of dose to activity given in previous paragraphs. It is assumed that the gonad dose and the effective dose equivalent have the same value. The annual collective effective dose equivalents obtained are 5, 33, and 17 man Sv for Switzerland, the United

Kingdom, and the United States, respectively. Translated into per caput annual effective dose equivalent, they become $8 \cdot 10^{-7}$, $6 \cdot 10^{-7}$, and $8 \cdot 10^{-8}$ Sv. The per caput annual effective dose equivalent for the United States population is underestimated because the ^{226}Ra -painted watches were assumed to be completely out of use. Taking an average value of $5 \cdot 10^{-7}$ Sv to be representative of the per caput annual effective dose equivalent to the world population, the annual collective effective dose equivalent for the world population is found to be of the order of 2000 man Sv.

(e) *Other radioluminous devices*

116. It is known that radioluminous materials are being used in exit signs, compasses, gun sights, telephone dials, and many other devices, but there is not enough information available to make a reasonable estimate of the doses arising from their use. However, it is likely that the resulting collective dose is insignificant in comparison to that from radioluminous timepieces.

2. Electronic and electrical devices

117. Electronic and electrical equipment may give rise to radiation exposure if they contain radioactive substances or if they emit x-radiation owing to the deceleration of electrons. Television sets belong to the second category and will be discussed later.

118. Radioactive materials provide pre-ionization in gases for the purpose of passing an electric current, so that the equipment reads faster and more reliably, or displays more constant characteristics [D4]. Examples of application are starters for tubular fluorescent lamps, trigger tubes in electrical appliances and excess-voltage protection devices. The radionuclides mainly used are ^{85}Kr , ^{147}Pm and ^{232}Th . Although the number of articles produced is very large, and the activities involved significant (see Table 22), the doses resulting from the normal use of such equipment can be expected to be very small. It is only in the event of breakage through accident or disposal that the radiation exposure could be significant.

3. Antistatic devices

119. Static eliminators containing radioactive substances are widely used in industry to reduce the electrical charge build-up on certain materials. The radiation ionizes the air around a charged object and thereby allows the charge to be neutralized.

120. Static eliminators using alpha particles emitted from ^{210}Po are also manufactured and sold to the general public in the United States. These devices are used to remove dust from phonograph records, photographic negatives and slides, lenses, etc. Each static eliminator nominally contains about 20 MBq of ^{210}Po at the time of manufacture [N6].

121. During the fabrication, polonium is interspersed in microspheres of ceramic material, which are then fixed to an aluminium backing plate with epoxy adhesive [N6]. The physical size of the microsphere is large enough so that the inhalation of the material is unlikely in case of loose contamination. If ingested, the microspheres are claimed to be insoluble in body fluids. The only significant hazard to the user seems to result

from external irradiation due to the very small gamma component of the ^{210}Po decay scheme. The corresponding annual whole-body dose was estimated to be about 10^{-8} Gy [N3]; the annual effective dose equivalent would be about 10^{-8} Sv.

122. In the United Kingdom, ^{210}Po static eliminators were subjected by the National Radiological Protection Board to routine leakage tests and to special tests intended to simulate severe but credible abuse and accident with these devices [W5]. Under severe conditions (impact and fire), the containment integrity of ceramic microspheres was found unsatisfactory and it was considered possible that ICRP dose limits could be approached or even exceeded.

4. Smoke detectors

123. Ionization chamber smoke detectors (ICSDs) use alpha radiation to cause ionization in the air between two electrodes, thereby allowing an electric current to flow across the air gap under the influence of a small potential. Combustion products entering the air gap become attached to the moving ions comprising the electric current. Current flow is thereby reduced, and the potential between the electrodes rises. These changes trigger an electronic circuit, and an alarm is released [N3, J6]. ICSDs provide an early warning of a fire condition.

124. Although some of the ICSDs now on the market contain ^{226}Ra , ^{238}Pu , ^{85}Kr , and ^{63}Ni , the preferred radionuclide is ^{241}Am . The use of ICSDs is widespread in industrial, commercial and public buildings, and also, at least in Canada and in the United States, in private homes. During the normal use of ICSDs, the doses to members of the public are virtually limited to those resulting from external irradiation.

125. Since 1972–1973 the residential market for ^{241}Am ICSDs has increased rapidly in the United States. Fourteen million units containing 1.5 TBq of ^{241}Am were distributed in 1978 and 26 million units have been distributed since 1972 [B5]. Belanger et al. [B5] have analysed the radiation impact resulting from manufacture, distribution, normal use and disposal of those 1.4×10^7 ICSDs. Assuming that their useful life is 10 years and that disposal is by either sanitary landfill or incineration, they calculated the collective whole-body dose to be 11 man Gy, most of it resulting from external irradiation during the useful life of the ICSD. The corresponding effective dose equivalent would be about 10 man Sv.

5. Ceramic, glassware, alloys, etc., containing uranium or thorium

126. The main uses of uranium in consumer products are either as a pigment [S9] or in applications making use of its high density. Thorium is used in incandescent mantles and in certain optical lenses.

127. The principal hazard from the uses of uranium and thorium under normal conditions is the external irradiation from the beta-emitting decay products. In general, doses received will be small due to substantial attenuation over the distance between the device and the exposed person. In particular cases, this may not apply, however. Some optical lenses containing up to

30% by weight of uranium or thorium may deliver substantial doses to the lens of the eye [W7]. The air absorbed dose rate at the surface of a lens which contained 18% thorium by weight was measured by thermoluminescent dosimetry to be 10^{-5} Gy h^{-1} [M11].

128. High concentrations of uranium and thorium are occasionally found in ophthalmic glass as a natural consequence of the glass manufacturing process [G12]. In the United States, the Optical Manufacturers Association issued a voluntary performance standard [O7] to establish a uniform maximum limit for radioactive emissions for ophthalmic glass. The standard states that the concentrations of ^{228}Ac , ^{212}Pb and ^{214}Pb in manufactured ophthalmic glass should not exceed 30 dpm g^{-1} (0.5 Bq g^{-1}). This limit could produce a maximum annual dose equivalent of about 5 mSv to the corneal germinal layer [G12].

129. Another example which has attracted interest is the practice of incorporating uranium in the porcelains used in restorative and prosthetic dentistry. In the United Kingdom, it is estimated that about one in nine adults has artificial porcelain teeth [O6]; in the United States, that proportion is likely to be even higher [S10]. A combination of uranium and cerium compounds is incorporated in the majority of modern porcelains in order to simulate the fluorescence of natural teeth in day light and in artificial light. As all the isotopes of uranium are radioactive, the tissues of the mouth are exposed to ionizing radiation from fluorescent porcelains.

130. An analysis performed by O'Riordan and Hunt [O6] on 20 porcelain powders under five brand names showed that 17 of the powders contained uranium, on the average 0.041% by weight, with 2 having about 0.1%. It is estimated in that study that for people with fluorescent porcelain teeth, the absorbed dose from external irradiation in the basal layer of the oral epithelium would be the limiting factor. Assuming a mass concentration of depleted uranium in the porcelain of 0.1%, the absorbed dose in that basal layer, taken to be at a distance of 30 μm from the interface, was found to be of the order of 0.03 Gy in a year. As the ranges of the alpha particles emitted by the isotopes of uranium are less than 30 μm in soft tissues, most of the absorbed dose is due to beta radiation. On the basis of that estimate, the National Radiological Protection Board has recommended that the use of radioactive fluorescers in dental porcelain be discontinued in the United Kingdom [O6]. Following that decision, the false-teeth industry in the United States voluntarily agreed to standardize the uranium content of porcelain at 0.025–0.03% by weight [W7].

131. In the Federal Republic of Germany and the United States, the two countries where most of the dental porcelain seems to be manufactured, the mass concentration of uranium is limited by law. The uranium content of porcelain powders and artificial teeth should not exceed 0.1% by weight in the Federal Republic of Germany and 0.05% in the United States. In the Federal Republic of Germany, an average concentration of uranium in porcelain of about 0.03% by weight was measured, none of the samples showing an uranium concentration in excess of 0.1% by weight [S15, S16]. In a recent survey conducted in Japan, the average uranium concentrations in four brands (one of which was from the United States) were found to be 0.0004%, 0.0009%, 0.002%, and 0.008%, the highest measured value being 0.02% [S17, S18].

B. OTHER MISCELLANEOUS SOURCES OF RADIATION

132. The general public may also be exposed to consumer products that do not contain radioactive materials but that emit x-radiation owing to the deceleration of electrons. The most familiar example of such consumer products is the television receiver. The exposures arising from the domestic use of television receivers, the inspection of hand luggage by x-ray equipment, and the use of x-ray tubes in secondary schools will be briefly discussed. Reference [N3] provides a more detailed treatment of the x-ray emitting consumer products.

133. As indicated in the 1972 UNSCEAR report [U6], several surveys conducted in the 1960s showed that a small proportion of the colour television sets emitted x-radiation in excess of the limit recommended by the ICRP, that is 0.5 mR h^{-1} (corresponding to $1.29 \cdot 10^{-7} \text{ C kg}^{-1} \text{ h}^{-1}$) at 5 cm from the surface of the television receiver. Modern television receivers have low x-ray emissions, as shown by several sets of data. This conclusion is supported by the results of measurements recently conducted in the Federal Republic of Germany [K10] and in Asia [W8]. In the first of these surveys, conducted in 1972, it was found that the average exposure rate 5 cm from the surface of the colour television receivers was about $3 \cdot 10^{-8} \text{ C kg}^{-1} \text{ h}^{-1}$ and that the estimated annual gonad dose, under normal viewing conditions, was of the order of $10 \text{ } \mu\text{Gy}$. Assuming that the effective dose equivalent (expressed in μSv) is approximately equal to the gonad dose (expressed in μGy), the corresponding annual effective dose equivalent would be about $10 \text{ } \mu\text{Sv}$. In the second survey the exposure rate at the surface of 28 randomly chosen colour television receivers was found to vary from about $3 \cdot 10^{-10}$ to $2 \cdot 10^{-8} \text{ C kg}^{-1} \text{ h}^{-1}$ under normal working conditions.

134. X-ray fluoroscopic scanning systems are used at most airports to inspect hand-carried baggage. The traveller often walks alongside the cabinet-type x-ray equipment as his or her luggage is being examined. The average exposure to the traveller per air trip due to the inspection of hand luggage was estimated in 1973 to be less than $4 \cdot 10^{-10} \text{ C kg}^{-1}$ in the United States [N3]. The corresponding effective dose equivalent is about 7 nSv .

135. Surveys conducted in Canada and in the United States in the early 1970s revealed that significantly large numbers of demonstration devices capable of emitting x rays were being used in secondary schools of those countries [Z1]. In Canada, exposure rates of up to $9 \cdot 10^{-3} \text{ C kg}^{-1} \text{ h}^{-1}$ were measured at a distance of 0.3 m from the surface of cold cathode x-ray tubes [Z1]. Assuming that the energy of the x rays involved is 50 keV , the

corresponding effective dose equivalent rate would be about 0.1 Sv h^{-1} . Most of the school teachers demonstrating the x-ray tubes had little or no knowledge of radiation protection principles or practices.

VII. SUMMARY

136. This Annex deals with some examples of technologically modified exposures to natural radiation which have been brought to the attention of the Committee. It is very likely that those examples do not present the complete picture of technologically modified exposures to natural radiation; indeed, the lack of rigour in the definition of such exposures (see paragraph 3) makes a comprehensive picture impossible. From the assessments presented at the current level of industrial and nuclear and coal cycle wastes utilization, the exposures do not add significantly to the collective effective dose equivalent on the global scale but may give rise, in localized areas or for people exposed under extreme conditions, to appreciable increases in individual exposures from natural radiation. The present state of knowledge does not allow an accurate estimate of the collective effective dose equivalent from technologically modified exposures to natural radiation to be made, and further measurements are required in this field.

137. Some examples of miscellaneous sources of radiation exposure have also been considered in this Annex. Many millions of units of various types of consumer products containing deliberately incorporated radionuclides are in everyday use around the world. Estimates of doses in individuals resulting from the use of such products show that in all cases these doses are small. The highest calculated effective dose equivalents result from the wearing of radioluminous watches, which are the most widespread radioactive consumer product. The assessment of the global collective effective dose equivalent from these sources is hampered by wide gaps in the knowledge of important factors such as the activities involved, the number of products on the market, and the problems related to the disposal of those devices. Even for the most common product, watches, the data are not always available since watches are generally not subject to control. Nevertheless, owing to international recommendations, and national regulations in some countries, there is a gradual improvement of control. It is likely that the average annual effective dose equivalent due to the use of consumer products is less than $10 \text{ } \mu\text{Sv}$, almost entirely due to radioluminous timepieces. However, in view of the growing number and diversity of consumer products, it is important to ensure that proper control is maintained over their use and disposal.

T a b l e 1
Activity concentration of radionuclides in coal samples
(Bq kg⁻¹)

Origin	238 _U decay series				232 _{Th} decay series		Ref.
	40 _K	238 _U	226 _{Ra}	210 _{Pb}	210 _{Po}	232 _{Th}	
Australia			30- 48				[B1]
Brazil	370		100			67	[S1]
Canada	440		30			26	[S1]
Czechoslovakia			4.1- 13				[J1]
China			7				[J1]
Germany, Fed. Rep. of							
Bituminous coal		< 40	20	25	30	< 20	[J8]
Brown coal		15	< 10	10	10	< 7	[J8]
Hungary			1.5				[J1]
India			25				[M12]
Italy							
Lignite from central Italy		15-25	4-15	25-50		70-110	[M1]
Lignite from Sardinia		250					[M1]
Poland							
Average	290	38				30	[T2]
Range	37-760	2-140				7-110	[T2]
South Africa	110		30			20	[S1]
USSR							
Average	120	28			22		[L4]
United Kingdom							
Average	120	17				17	[H3]
Range		11-29	7.4-94			2.4-19	[C4]
United States							
West	110	20	16	17		13	13
Illinois and Kentucky	44	27				8.5	
Alabama, Tennessee, Kentucky	120		8.9			27	
Wyoming 1			0.52	10			
Wyoming 2		18		31	41		
Appalachia, Illinois, Montana, Pennsylvania, and Wyoming	70	16	14			8.9	
Country average ^{a/}	52	18				21	
Venezuela	110		< 20			< 20	

a/ Arithmetic mean activity concentrations of 910 samples of coal originating from several United States mines. The results, given in reference [B2], are compiled from data contained in references [F2], [G2], and [S3].

Table 2

Activity concentrations of natural radionuclides in ash samples
(Bq kg⁻¹)

Type of ash and origin	²³⁸ U decay series				²³² Th decay series			Ref.	
	⁴⁰ K	²³⁸ U	²²⁶ Ra	²¹⁰ Pb	²¹⁰ Po	²³² Th	²²⁸ Th		²²⁸ Ra
BOTTOM ASH (slag)									
Australia			250						[B1]
Germany, Fed.Rep.of	(1)		130				96		[J3]
	(2)	520	170 a/				140		[S1]
Japan									
Central			4	740			560	44	[N1]
Southern			37	300			90	20	[N1]
Northern			20	3900			250	55	[N1]
Poland									
Average	500	48				44			[T2]
Range	280-1200	17-100				15-120			[T2]
USSR	370		78		7.4	70			[L4]
United States									
West	240	81	81	30		67		67	[C1]
Ill. and Kent.	480	180				59			[K2]
Pennsylvania	480	67	59			52			[B2]
Wyoming 1			20	37					[S2]
Wyoming 2		93		210	190				[S2]
FLY-ASH (collected)									
Germany, Fed.Rep.of									
Bituminous coal		300	200	2000	2000	100			[J7]
Brown coal		70	40	60	100	30			[J7]
India			100					130	[M12]
Italy									
Central		80-100	40-70	44-330		300			[M1]
Sardinia		1000							[M1]
Poland									
Average	730	97				74			[T2]
Range	180-1500	44-170				33-130			[T2]
United States									
Appalachia 1			140			96		89	[E1]
Appalachia 2	780		70			52			[B3]
Appalachia 3	410		100			44		44	[G3]
Appalachia 4	700	96	90			89			[B2]
Ill. and Kent.	590	130				81			[K2]
Pennsylvania	700	85	85			78			[B2]
Wyoming 1			30	370	480				[K1]
Wyoming 2		160		210	200				[S2]
West	260	110	100	78		81		81	[C1]
Appalachia, Midwest and West	480	89				170			[F1]
FLY-ASH (escaping)									
Australia			520						[B1]
Germany, Fed. Rep. of									
Bituminous coal		300	300	3000	5500	100			[J7]
Brown coal		100	70	200	300	40			[J7]
Hungary			20-560						[P2]
United States									
West b/	260-270			160-630			100-120	100-160	[C1]
Wyoming 1			15	630	700				[K1]
Wyoming 2 c/		200		410	250				[S2]

a/ Derived from the assumption that radium-228 is in radioactive equilibrium with thorium-228.

b/ Range of values obtained for four different size fractions (2.4 to 18.5 µm mass median diameter).

c/ Derived from the assumption that the enrichment between collected and escaping fly-ash is equal to 1.3 for uranium-238.

Table 3

Measured enrichment factors in escaping fly-ash
[B2]

Uranium	Enrichment factor in escaping fly-ash					Percentage of fly-ash released	Ref.
	²²⁶ Ra	²¹⁰ Pb	²¹⁰ Po	Thorium	²²⁸ Ra		
1.3	1-2	1-5	-	1.0-1.2	1.0-1.6	< 3	[C1] a/
-	1.7 b/	11 c/	-	1.4	1.7 b/	0.47	[K2]
-	-	1	-	-	-	3.5	[K2]
-	1	5	5	-	-	4.8	[K1]
-	2	-	-	-	-	7.5	[B1]
-	-	6-10 c/	-	-	-	-	[N2] d/

- a/ Range for various size fractions; the variation with size is presented in Figure 1.
b/ Estimate of Beck et al. [B2] from measurement of barium.
c/ Measurements for stable lead.
d/ Range of composite samples of different size fractions from 8 power plants; maximum enrichment for particles of 1-2 µm diameter.

Table 4

Estimates of average activity concentrations of natural radionuclides
in escaping fly-ash and of annual atmospheric discharges
per unit energy generated

Origin	²³⁸ U decay series				²³² Th decay series			Ref.	
	⁴⁰ K	²³⁸ U	²²⁶ Ra	²¹⁰ Pb	²¹⁰ Po	²³² Th	²²⁸ Ra		²²⁸ Th
ACTIVITY CONCENTRATIONS IN ESCAPING ASH (Bq kg ⁻¹)									
UNSCAR, 1977 report	600	200	40	400	400	40	40	40	[U2]
Averages of Table 2	265	200	240	930	1700	70	130	110	
Adopted values	500	200	200	600	600	200	200	200	
ESTIMATED ATMOSPHERIC DISCHARGES per unit energy generated (MBq per GW a)									
France 1981	3500	7000	7000			6000			[A4]
Germany, Fed.Rep., 1981									
Brown coal		100	70	200	400	40	40	40	[J7, S19]
Bituminous coal		500	500	4000	8000	200	200	200	[J7]
Bituminous dry ash removal		300	200	200	300	100	200	100	[H4]
Bituminous liquid ash removal		500	300	2000	6000	200	200	200	[H4]
India 1980			11000				15000		[M12]
Italy (1) a/ 1979		4400	4400	15000		18000			[H1]
(2)		18000	18000	26000		26000			[M1]
USSR 1978	20000		2000	8100	7400	2000	1100		[I1]
United Kingdom 1980	1000	1000	1000	1000	1000	1000	1000	1000	[C4]
United States, 1964			640				400		[E1]
1970		270	270			300	300		[H2]
1977		300	300	300	300	200	200	200	[M3]
1977		4900	5600			6300	6300	6300	[N3]
b/ 1977	670-	150-	140-	670-	670-	110-	110-	110-	[L2]
c/ 1977	2000	410	410	2000	2000	370	370	370	
d/ 1977	1100	1000	780	2600	2600	410	410	410	[B2]
d/ 1977	10000	4700	4700	9300	9300	3800	3800	3800	[B2]
UNSCAR, 1977 report		5500	1850	370	3700	3700	370	370	[U2]
This report		4000	1500	1500	5000	5000	1500	1500	

- a/ The two plants considered burn lignite of low heat content, high ash fractions, and high activity content, resulting in elevated discharges.
b/ Range of releases reported for plants burning different types of coal.
c/ Modern plant.
d/ 1972 reference plant.

Table 5

Committed doses per unit activity inhaled ($\mu\text{Gy Bq}^{-1}$)
of the most important natural radionuclides released from coal-fired power plants
[J7]

Organ or tissue	Uranium decay series						Thorium decay series				
	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{222}Rn a/ and daughters	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{220}Rn and daughters
Lungs	5.5	6.6	6.0	0.4	0.0093 (T-B) 0.0012 (P)	0.2	0.5	26	0.2	15	0.011
Bone surfaces	0.06	0.07	46	0.17	-	0.8	0.01	240	0.15	20	0.013
Red bone marrow	0.004	0.004	3.6	0.015	-	0.085	0.01	20	0.015	1.7	0.001
Liver	0.0001	0.0001	0.075	0.002	-	0.35	0.01	0.065	0.004	0.15	0.002
Kidneys	0.025	0.029	0.01	0.002	-	0.17	0.25	0.007	0.004	0.02	0.008
Spleen	0.0001	0.0001	0.01	0.002	-	0.03	0.45	0.007	0.004	0.02	0.0003
G.I. tract	0.0007	0.0008	0.01	0.003	-	0.006	0.006	0.008	0.004	0.025	-
Other soft tissues	0.0001	0.0001	0.01	0.002	-	0.01	0.01	0.007	0.004	0.02	0.0001
Effective dose equivalent per unit activity inhaled ($\mu\text{Sv Bq}^{-1}$)	13	15	51	1.1	0.013	2.0	2.2	250	0.61	51	0.051

a/ The committed doses and effective dose equivalents per unit activity inhaled of the short-lived decay products of the radon isotopes are estimated from data in Annex D. For the radon-222 daughters the effective dose equivalent is obtained from the absorbed doses in the bronchial basal cell layer (T-B) and the pulmonary epithelium (P). Only the doses due to the α particles are taken into account.

Table 6

Estimates of collective dose commitments per unit energy generated
resulting from atmospheric releases from coal-fired power plants
(10^{-3} man Gy per GW a)

Inhalation during the passage of the cloud.

Organ or tissue	Uranium decay series						Thorium decay series				Total (rounded)
	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{222}Rn and daughters a/	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	
Lungs	19	23	21	1.4	0.69 (T-B) 0.09 (P)	2.3	5.8	90	0.7	52	210
Bone surfaces	0.2	0.2	160	0.6	-	9.2	0.1	830	0.5	69	1070
Red bone marrow	0.01	0.01	12	0.05	-	0.1	0.1	69	0.05	5.9	89
Liver	0.0003	0.0003	0.3	0.007	-	4.0	0.1	0.2	0.01	0.5	5
Kidneys	0.09	0.1	0.03	0.007	-	2.0	2.9	0.02	0.01	0.07	5
Spleen	0.0003	0.0003	0.03	0.007	-	0.3	5.2	0.02	0.01	0.07	6
G.I. tract	0.002	0.003	0.03	0.01	-	0.07	0.07	0.03	0.01	0.09	0.3
Other soft tissues	0.0003	0.0003	0.03	0.007	-	0.1	0.1	0.02	0.01	0.07	0.4
Collective effective dose equivalent commitment per unit energy generated (10^{-2} man Sv (GW a) $^{-1}$)	4.5	5.2	18	0.4	0.1	2.3	2.5	86	0.2	18	140

a/ T-B and P stand for bronchial basal cell layer and pulmonary epithelium, respectively.

T a b l e 7

Estimates of collective dose commitments per unit energy generated
resulting from atmospheric releases from coal-fired power plants

(10^{-3} man Gy per GW a)

External and internal irradiation due to the activity deposited.

	Uranium decay series					Thorium decay series			Total (rounded) a/	
	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{222}Rn and daughters a/	^{210}Pb and ^{210}Po	^{232}Th	^{228}Ra and daughters		^{220}Rn and daughters
Internal irradiation										
Lungs	0.2	0.1	0.6	0.2	140 (T-B) 19 (P)	5.2	0.5	3.0	20	170 (T-B) 49 (P)
Bone surfaces	2.6	2.4	8.9	6.8	-	69	2.4	5.5	24	120
Red bone marrow	0.4	0.3	0.7	0.7	-	12	0.2	0.5	1.9	17
Liver	0.2	0.1	0.008	0.2	-	9.7	0.5	1.0	3.6	15
Kidneys	1.6	1.4	0.3	0.2	-	9.7	0.7	1.9	14	30
Other soft tissues	0.2	0.1	0.008	0.2	-	9.7	0.004	0.1	0.2	11
Collective effective dose equivalent commitment per unit energy generated (10^{-2} man Sv/(GW a) $^{-1}$)										
	0.6	0.6	0.9	0.9	20	22	0.3	1.6	9.4	56
External irradiation										
All tissues	35					54				90
										(10^{-3} man Gy (GW a) $^{-1}$)

a/ T-B and P stand for bronchial basal cell layer and pulmonary epithelium, respectively.

T a b l e 8

Estimates of collective effective dose equivalent commitments
per unit energy generated
resulting from atmospheric releases from coal-fired power plants

(10^{-2} man Sv per GW a)

Radio-nuclide	Inhalation during the cloud passage	Internal irradiation due to the activity deposited	External irradiation due to the activity deposited	Total
^{238}U	4	0.6] 4]	82
^{234}U	5	0.6		
^{230}Th	18	0.9		
^{226}Ra	0.4	0.9		
^{222}Rn +daughters	0.1	20		
^{210}Pb + ^{210}Po	5	22		
^{232}Th	86	0.3] 5]	120
^{228}Ra +daughters	18	2		
^{220}Rn +daughters	-	9		
Total (rounded)	140	56	9	200

Table 9

Production of phosphate rock in 1977
and reported activity concentrations of natural radionuclides

	Production of marketable rock in 1977		Activity concentrations (Bq kg ⁻¹)				Ref.
	(10 ⁹ kg)	Percentage of the world production	²³⁸ U	²²⁶ Ra	²³² Th	⁴⁰ K	
WORLD	125.7	100					
China a/	4.1	3.3	150	150	25		[15]
Christmas Islands	1.3	1.0	330	300	7		[15]
Israel	1.2	1.0	1500-1700				[D3]
Jordan	1.8	1.4	1300-1850				[D3]
Morocco (1)	17.6	14.0	1700	1700	30		[15]
(2)			1500	1500	30	200	[C2]
(3)			1700	1570	20	10	[P6]
Nauru	1.1	0.9	810	850	7		[15]
Senegal b/	1.8	1.4	1300	1400	67		[15]
Togo	2.9	2.3	1300	1200	110	≤ 100	[C2]
Tunisia	3.6	2.9	590	520	92		[15]
USSR	24.2	19.3					
Kola, apatite (1)			90	40	91	170	[C2]
(2)			70	70	92		[15]
(3)			44	30	78	44	[P6]
Kola, phosphorite				390	25	230	[G6]
United States	47.3	37.6					
Central Florida (1)			1500	1600	16		[14]
Central Florida (2) (pebble)			1700	2100			[R4]
North Florida, pebble			800	1000			[R4]
Florida, land pebble and soft phosphate			1900	2000	59		[15]
Florida			1300	1270	30	48	[P6]
Arkansas			370	410	52		[15]
Idaho			1850	1800	30		[15]
Montana			1400	1500	25		[15]
North Carolina			960	670	40		[15]
Oklahoma			300	370	30		[15]
South Carolina			4800	4800	78		[15]
Tennessee, brown rock, blue rock, white rock, phosphatic limestone			150	150	20		[15]
Utah			1600	1850	30		[15]
Wyoming			2300	2300	10		[15]
Viet Nam	1.5	1.2					[15]

a/ Samples from China, India, and South-East Asia.

b/ Samples from Senegal and other African countries.

T a b l e 10

Data on discharges from phosphate industry operations

Type of plant	Annual input of marketable ore (10 ⁹ kg) a/	238 _U	230 _{Th}	226 _{Ra}	232 _{Th}	Ref.
Airborne annual discharges (MBq)						
Ore drying plant	2.7	245	250	250		[P4]
Wet process phosphoric acid plant						
Plant A	1.2	9.2	8.7	6.8		[P4]
Plant B b/	1.2	1300	1200	540		[P4]
Uranium recovery plant	0.4	350	small	small	small	[D2]
Activity concentrations in liquid discharges (Bq m ⁻³)						
Phosphate mine and beneficiation plant						
Heavy slime: undissolved				2500(400-80000)		[G4]
dissolved				65(20-80)		[G4]
Effluent: undissolved				20(5-40)		[G4]
dissolved				30 (1-80)		[G4]
Wet process phosphoric acid plant						
Plant 1: Field survey number 1						
Untreated process water		39000	2600	3000	170	[G4]
Outfall (after chemical treatment)		20	20	170	1.5	[G4]
Field survey number 2						
Untreated process water		15000	3700	2000	120	[G4]
Outfall (after chemical treatment)		620	30	70	4	[G4]
Plant 2:						
Untreated process water		68000	15000	3200	230	[G4]
Outfall (after chemical treatment)		12	5	17	ND	[G4]
Plant 3:						
Untreated process water		24000	320	2000	150	[G4]
Outfall (after chemical treatment)		10	ND	94	ND	[G4]

a/ Reported or estimated.

b/ The airborne discharges from plant B are very uncertain and likely to be overestimates.

T a b l e 11

Estimated distribution of the activity (TBq) present
in the phosphate fertilizers
produced in the United States during 1974
[G4]

Material	Mass		Activity (TBq)			
	(10 ⁹ kg)	(10 ⁹ kg P ₂ O ₅)	226 _{Ra}	238 _U	230 _{Th}	232 _{Th}
Marketable ore used for fertilizer production	25.6	8.0	40	39	40	0.4
Normal superphosphate	3.1	0.6	2.4	2.3	2.1	0.07
Concentrated superphosphate	3.4	1.6	2.6	7.0	5.9	0.04
Ammonium phosphates a/	5.3	2.4	1.1	13	13	0.07
Phosphoric acid	10.0	3.1	0.37	9.4	10	1.1
Other fertilizer production	2.0	0.3				
Gypsum	25.2		31	5.7	12	0.3

a/ Does not include phosphoric acid used to produce diammonium phosphates and concentrated superphosphates.

T a b l e 12

Estimates of collective dose commitments per unit mass of phosphate ore
due to atmospheric releases from phosphate industry plants:
doses arising from inhalation during the cloud passage

Radio-nuclide	Airborne discharge (Bq t ⁻¹)	Collective dose commitments per unit mass of phosphate ore (10 ⁻⁹ man Gy t ⁻¹)							
		Lungs a/	Bone surfaces	Red bone marrow	Liver	Kidneys	Spleen	G.I. tract	Other soft tissues
Ore drying plant									
²³⁸ U	90	1.1	0.01	0.0009	0.00002	0.005	0.00002	0.0001	0.00002
²³⁴ U	90	1.4	0.01	0.0009	0.00002	0.006	0.00002	0.0002	0.00002
²³⁰ Th	90	1.2	9.5	0.7	0.02	0.002	0.002	0.002	0.002
²²⁶ Ra	90	0.08	0.04	0.003	0.0004	0.0004	0.0004	0.0006	0.0004
²²² Rn	1.5 10 ⁶	[17 (T-B) 2.2 (P)	-	-	-	-	-	-	-
Total		[17 (T-B) 6.0 (P)	9.6	0.7	0.02	0.01	0.002	0.003	0.002
Wet process phosphoric acid plant (Plant A)									
²³⁸ U	7	0.09	0.001	0.00006	0.000002	0.0004	0.000002	0.00001	0.000002
²³⁴ U	7	0.1	0.001	0.00006	0.000002	0.0005	0.000002	0.00001	0.000002
²³⁰ Th	7	0.1	0.7	0.06	0.001	0.0002	0.0002	0.0002	0.0002
²²⁶ Ra	6	0.006	0.002	0.0002	0.00003	0.00003	0.00003	0.00004	0.00003
²²² Rn	1.5 10 ⁶	[17 (T-B) 2.2 (P)	-	-	-	-	-	-	-
Total		[17 (T-B) 2.5 (P)	0.7	0.06	0.001	0.001	0.0002	0.0003	0.0002
Wet process phosphoric acid plant (Plant B)									
²³⁸ U	1000	13	0.1	0.009	0.0002	0.06	0.0002	0.002	0.0002
²³⁴ U	1000	15	0.2	0.009	0.0002	0.07	0.0002	0.002	0.0002
²³⁰ Th	960	13	100	8.0	0.2	0.02	0.02	0.02	0.02
²²⁶ Ra	440	0.4	0.2	0.02	0.002	0.02	0.002	0.003	0.002
²²² Rn	1.5 10 ⁶	[17 (T-B) 2.2 (P)	-	-	-	-	-	-	-
Total		[17 (T-B) 44 (P)	100	8.0	0.2	0.2	0.02	0.03	0.02
Uranium recovery plant									
²³⁸ U	850	11	0.1	0.008	0.0002	0.05	0.0002	0.001	0.0002
²³⁴ U	850	13	0.1	0.008	0.0002	0.06	0.0002	0.002	0.0002
Total		24	0.2	0.02	0.0004	0.1	0.0004	0.003	0.0004

a/ T-B and P stand for bronchial basal cell layer and pulmonary epithelium, respectively.

T a b l e 13

Estimates of collective dose commitments per unit mass of phosphate ore due to atmospheric releases from phosphate industry plants: doses due to the activity deposited

Radio-nuclide	Airborne discharge (Bq t ⁻¹)	Collective dose commitments per unit mass of phosphate ore (10 ⁻⁹ man Gy t ⁻¹)						
		External irradiation	Internal irradiation					
			All tissues	Lungs a/	Bone surfaces	Red bone marrow	Liver	Kidneys
Ore drying plant								
²³⁸ U	90	2.1	0.009	0.2	0.03	0.009	0.09	0.009
²³⁴ U	90		0.009	0.1	0.02	0.009	0.09	0.009
²³⁰ Th	90		0.03	0.5	0.04	0.0005	0.02	0.0005
²²⁶ Ra	90		0.01	0.4	0.04	0.01	0.01	0.01
²²² Rn			[8.6 (T-B) 1.2 (P)	-	-	-	-	-
Total			[8.6 (T-B) 1.3 (P)	1.2	0.1	0.03	0.2	0.03
Wet process phosphoric acid plant (Plant A)								
²³⁸ U	7	0.1	0.0007	0.01	0.002	0.0007	0.008	0.0007
²³⁴ U	7		0.0007	0.01	0.001	0.0007	0.007	0.0007
²³⁰ Th	7		0.003	0.04	0.003	0.00004	0.001	0.00004
²²⁶ Ra	6		0.0008	0.03	0.003	0.0008	0.0009	0.0009
²²² Rn			[0.6 (T-B) 0.08 (P)	-	-	-	-	-
Total			[0.6 (T-B) 0.09 (P)	0.09	0.009	0.002	0.02	0.002
Wet process phosphoric acid plant (Plant B)								
²³⁸ U	1000	10	0.1	1.8	0.3	0.1	1.0	0.1
²³⁴ U	1000		0.1	1.6	0.2	0.1	1.0	0.1
²³⁰ Th	960		0.4	5.7	0.4	0.005	0.2	0.005
²²⁶ Ra	440		0.06	2.0	0.2	0.06	0.06	0.06
²²² Rn			[42 (T-B) 5.6 (P)	-	-	-	-	-
Total			[42 (T-B) 6.3 (P)	11	1.1	0.3	2.3	0.3
Uranium recovery plant								
²³⁸ U	850	-	0.09	1.5	0.2	0.09	0.9	0.09
²³⁴ U	850	-	0.08	1.4	0.2	0.08	0.8	0.08
Total			0.2	2.9	0.4	0.2	1.7	0.2

a/ T-B and P stand for bronchial basal cell layer and pulmonary epithelium, respectively.

T a b l e 14

Activity concentrations of naturally occurring radionuclides
in phosphate fertilizers
(Bq kg⁻¹)

Type of fertilizer	Country	²³⁸ U	²³⁰ Th	²²⁶ Ra	²¹⁰ Pb	²¹⁰ Po	²³² Th	⁴⁰ K	Ref.
TREATED ROCK PHOSPHATES									
Apatite	USSR			30	25	30	60	100	[G6]
Phosphorite	USSR			390	380	480	25	230	[G6]
Concentrate obtained by flotation	USSR			420	390	290	20	73	[G6]
Calcined, ground soft, partly converted rock phosphate, etc. <u>a/</u>	FRG <u>b/</u>	670		480			25	110	[P6]
ONE-COMPONENT PHOSPHATE FERTILIZERS									
Superphosphate	FRG <u>b/</u>	529		520			15	140	[P6]
Superphosphate	USSR			110	300	150	44	120	[G6]
Superphosphate	USA <u>c/</u>	740	670	790			20		[H4]
Superphosphate	Belgium	1100		910			<25	<180	[C2]
Triple superphosphate	FRG <u>b/</u>	800		230			44	52	[P6]
Triple superphosphate	USA	2100	1800	780			48		[H4]
PK-FERTILIZERS <u>d/</u>	FRG <u>b/</u>	410		370			15	5900	[P6]
NP-FERTILIZERS									
NP-fertilizers <u>a/</u>	FRG <u>b/</u>	920		310			30	41	[P6]
Ammonium phosphate	USSR			100			48		[G6]
Nitrophosphate	USSR			850	870	920	10		[G6]
Nitroammonium phosphate	USSR				15	15	30		[G6]
Monoammonium phosphate	USA	2000	1800	20			63		[H4]
Diammonium phosphate	USA	2300	2400	210			15		[H4]
NPK-FERTILIZERS <u>e/</u>									
NPK	FRG <u>b/</u>	440		270			15	5200	[P6]
NPK	USSR			9	15	20	54	1200	[G6]
NPK	Belgium	470		210			<15	5900	[C2]
BASIC SLAG	Belgium	23		19					[K4]

a/ Assuming a P₂O₅-to-fertilizer mass concentration ratio of 0.28.

b/ Federal Republic of Germany.

c/ United States.

d/ Assuming a P₂O₅-to-fertilizer mass concentration ratio of 0.16.

e/ Assuming a P₂O₅-to-fertilizer mass concentration ratio of 0.13.

T a b l e 15

Estimated collective dose commitment per unit mass of marketable rock
arising from the use of phosphate fertilizers
(10⁻⁷ man Gy t⁻¹)

	²³⁸ U	²³⁴ U	²³⁰ Th	²²⁶ Ra	²²² Rn	²¹⁰ Pb	Total
Internal irradiation							
Lungs	0.3	0.3	1.1	0.3	¹⁹⁰ (T-B) ₂₆ (P)	5.0	¹⁹⁰ (T-B) ₃₃ (P)
Bone surfaces	5.3	4.8	18	9.0		66	100
Red bone marrow	0.9	0.6	1.3	0.9		11	15
Liver	0.3	0.3	0.02	0.3		9.3	10
Kidneys	3.1	2.9	0.6	0.3		9.3	16
Other tissues	0.3	0.3	0.02	0.3		9.3	10
External irradiation							
All tissues	1.5						1.5

Table 16

Estimates of collective effective dose equivalent commitments
per unit mass of marketable ore
due to the exploitation of phosphate rock
(10^{-6} man Sv t⁻¹)

Source of exposure	Cloud passage Inhalation	Activity deposited		Total
		Internal irradiation	External irradiation	
Atmospheric discharges from an ore drying plant	0.04	0.01	0.002	0.05
Atmospheric discharges from wet process phosphoric acid plant A	0.03	0.0009	0.0001	0.03
Atmospheric discharges from wet process phosphoric acid plant B	0.2	0.06	0.01	0.3
Atmospheric discharges from an uranium recovery plant	0.05	0.007	-	0.06
Agricultural use of phosphate fertilizers	-	50	15	65
		Internal irradiation	External irradiation	Total
Use of by-product gypsum as building material in homes		17000	16000	33000

Table 17

Activity concentration of naturally occurring radionuclides
in building materials
expected to give rise to higher-than-average external absorbed doses

Type of building material	Country	No. of samples b/	Average activity concentration (Bq kg ⁻¹)			Absorbed dose rate in air a/ Ref. (10 ⁻⁸ Gy h ⁻¹)
			⁴⁰ K	²²⁶ Ra	²³² Th	
<u>Natural origin</u>						
Granite	FRG	34	1200	100	80	30 [S5]
Granite bricks	UK	7	1000	90	85	28 [H1]
Granite	USSR	2	1500	110	170	45 [K6]
Lithoid tuff	Italy	-	1500	130	120	40 [N5]
Pumice stone	FRG	20	1100	130	130	35 [S5]
Concrete containing alum shale	Sweden	83	850	1500	70	145 [S6]
<u>Industrial origin</u>						
Phosphogypsum from phosphorite	FRG	39	110	600	<5	54 [S5]
Phosphogypsum	UK	6	70	800	20	68 [H1]
Phosphogypsum	USA	-	-	1500	7	126 [G6]
Calcium silicate slag	Canada	-	-	2150	-	184 [P5]
Calcium silicate slag	USA	-	-	1300-1500	-	110-130 [B4]
Red-mud bricks	FRG	23	330	280	230	58 [S5]
Fly-ash	FRG	28	700	210	130	42 [S5]
Fly-ash type 1	UK	1	550	7	40	10 [H1]
type 2	UK	1	550	140	30	20 [H1]
type 3	UK	1	220	50	44	12 [H1]
Blast-furnace slag	USSR	29	240	70	20	11 [K6]
Slag aggregate c/	Finland	3	190	100	70	19 [H5]

a/ The absorbed dose rates in air have been calculated assuming a 4 π geometry and an infinite thickness of material. The values obtained are an index allowing the comparison between building materials and not an estimate of the doses that would be received in dwellings constructed with those building materials.

b/ Federal Republic of Germany = FRG; United Kingdom = UK; United States = USA.

c/ Mixture of coal clinker, ash, and cement.

T a b l e 18

Variation of the galactic dose rate
and dose equivalent rate with altitude a/
[04]

Altitude (km)	Absorbed dose rate ($\mu\text{Gy h}^{-1}$)	Dose equivalent rate ($\mu\text{Sv h}^{-1}$)
4	0.14	0.20
6	0.33	0.51
8	0.84	1.35
10	1.75	2.88
12	3.01	4.93
14	4.62	7.56
16	5.92	9.70
18	7.09	11.64
20	7.72	12.75

a/ Values averaged over 2 geomagnetic latitudes (43° and 55°) and over two periods of solar activity (minimum and maximum).

T a b l e 19

Comparison of calculated cosmic-ray doses
to a person flying in subsonic and supersonic aircraft
(average solar conditions)
[W2]

Route	Subsonic flight at 11 km		Supersonic flight at 19 km	
	Flight duration (h)	Dose per round trip (10^{-5} Gy)	Flight duration (h)	Dose per round trip (10^{-5} Gy)
Los Angeles - Paris	11.1	4.8	3.8	3.7
Chicago - Paris	8.3	3.6	2.8	2.6
New York - Paris	7.4	3.1	2.6	2.4
New York - London	7.0	2.9	2.4	2.2
Los Angeles - New York	5.2	1.9	1.9	1.3
Sydney - Acapulco	17.4	4.4	6.2	2.1

T a b l e 20

Absorbed dose rates of astronauts on space missions
[C3, E2, R7, G9]

Mission or mission series	Launch date	Duration of mission (h)	Type of orbit	Dose (10^{-5} Gy)
Apollo VII	Aug. 1968	260	Earth orbital	120
Apollo VIII	Dec. 1968	147	Circumlunar	185
Apollo IX	Feb. 1969	241	Earth orbital	210
Apollo X	May 1969	192	Circumlunar	470
Apollo XI	July 1969	182	Lunar landing	200
Apollo XII	Nov. 1969	236	Lunar landing	~ 200
Apollo XIV	Jan. 1971	209	Lunar landing	~ 500
Apollo XV	July 1971	286	Lunar landing	~ 200
Vostok 1-6			Earth orbital	2-80
Voskhod 1, 2			Earth orbital	30,70
Soyuz 3-9			Earth orbital	62-234

T a b l e 21

Breakdown of the absorbed dose and dose equivalent
on spacecraft mission Apollo XI
[E2]

Component	Absorbed dose (10 ⁻⁵ Gy)	Dose equivalent (10 ⁻⁵ Sv)
Protons	150	220
Stars	15	94
Fast neutrons	~ 1	~ 12
Heavy nuclei	5	46
Electrons and gamma rays	~ 30	~ 30
TOTAL (rounded)	200	400

T a b l e 22

Consumer products in the Federal Republic of Germany
[W3]

*The data refer to the years 1973 or 1975,
depending on the product.*

Type of consumer product	Produced in the Fed. Rep. of Germany			Number of pieces imported into the Fed.Rep.of Germany
	Number of pieces or weight	Total activity and radionuclide used	Exported	
<u>Radioluminous timepieces</u>				
Devices containing scales or dials with luminous paint	14 10 ⁶	40 TBq ³ H 10 TBq ¹⁴⁷ Pm	50 %	8 10 ⁵ (³ H) 1 10 ⁵ (¹⁴⁷ Pm)
<u>Electronic and electrical devices</u>				
High-pressure mercury lamps	7 10 ⁶	15 GBq ²³² Th	20 %	
Ignition devices for fluorescent lamps	26 10 ⁶	3 TBq ⁸⁵ Kr	50 %	
Electronic components containing radioactive substances	40 10 ⁶ 11 10 ⁶ 3 10 ⁶	200 TBq ⁸⁵ Kr 10 TBq ³ H or ¹⁴⁷ Pm 0.2 GBq ²³² Th	40 %	3 10 ⁴
Electronic tubes	7 10 ⁵	³ H, ⁶⁰ Co, ⁶³ Ni ¹⁴⁷ Pm, ²²⁶ Ra		
Antistatic devices	?	²¹⁰ Po		
<u>Smoke detectors</u>	1 10 ⁵	²²⁶ Ra, ²⁴¹ Am		
<u>Ceramic, glassware, alloys, etc. containing uranium or thorium</u>				
Articles with uranium paints	3 10 ⁵	0.6 GBq ²³⁸ U	50 %	1 10 ⁶
Glassware containing uranium	4 10 ³ kg	2 GBq ²³⁸ U	50 %	3 10 ⁵
Glassware containing thorium	16 10 ³ kg	7 GBq ²³² Th	10 %	

T a b l e 23

Estimated number of radioluminous timepieces
in use in the various countries

Country	Year	Watches (10 ⁶)			Clocks (10 ⁶)			Ref.
		³ H	¹⁴⁷ Pm	²²⁶ Ra	³ H	¹⁴⁷ Pm	²²⁶ Ra	
Switzerland	1976	2.6	0.64	0.07	1.4	1.6	0.38	[K9]
United Kingdom	1978	5		0.8				[T1]
United States	1977	27	0.21	negli- gible	0.98	2.3	8.4	[M8]

REFERENCES

- A1 Abernethy, R.R. and F.H. Gibson. Rare elements in coal. p. 6069 in: Bureau of Mines Report I.C.-8163. U.S. Department of Interior, Washington, D.C., 1963.
- A2 Anonymous. Increased risk of cancer found in Florida homes of phosphate lands. *Environm. Health Letter* 18: 3-4 (1979).
- A3 Adams, N., B.W. Hunt and J.A. Reissland. Annual limits of intake of radionuclides for workers. NRPB-R82 (1978).
- A4 Aigueperse, J., J. Chalabreysse, R. Coulon et al. Impact radiologique des rejets atmospheriques d'une centrale au charbon. p. 195-214 in: *Health Impacts of Different Sources of Energy*. IAEA, Vienna, 1982.
- A5 Annanmäki, M. Measurements of radon in Finnish dwellings. Fifth Meeting of the Nordic Society of Radiation Protection. Visby, September 1978. Institute of Radiation Protection, Helsinki (1978).
- B1 Bayliss, R.J. and H.W. Whaite. A study of the radium alpha-activity of coal, ash and particulate emission at a Sydney power station. *Air and Wat. Pollut. Int. J.* 10: 813-819 (1966).
- B2 Beck, H.L., C.V. Gogolak, K.M. Miller et al. Perturbations on the natural radiation environment due to the utilization of coal as an energy source. p. 1521-1558 in: *Natural Radiation Environment III*. CONF-780422 (Vol.2) (1980).
- B3 Bedrosian, P.H., D.G. Easterly and S.L. Cummings. Radiological survey around power plants using fossil fuel. EERL-71-3 (1970).
- B4 Booth, G.F. The need for radiation controls in the phosphate and related industries. *Health Phys.* 32: 285-290 (1977).
- B5 Belanger, R., D.W. Buckley and J.B. Swensen. Environmental assessment of ionization chamber smoke detectors containing Am-241. NUREG CR-1156 (1979).
- B6 Blackburn, R. and J. Gueran. Annual rate of release of radon to the atmosphere as a result of coal combustion in the United Kingdom. *Radiation Phys. Chem.* 13: 145-147 (1979).
- C1 Coles, D.G., R.C. Ragaini and J.M. Ondov. Behaviour of natural radionuclides in western coal-fired power plants. *Environ. Sci. Technol.* 12: 442-446 (1978).
- C3 Curtis, S.B. Radiation physics and evaluation of current hazards. in: *Space Radiation Biology and Related Topics*. (C.A. Tobias and P. Todd, eds.) Academic Press, 1974.
- C4 Camplin, W.C. Coal-fired power stations—the radiological impact of effluent discharges to atmosphere. NRPB-R107 (1980).
- C5 Chatterjee, B., H. Hötzl, G. Rosner et al. Untersuchungen über die Emission von Radionukliden aus Kohlekraftwerken; Analysenverfahren und Messergebnisse für ein Steinkohle- und ein Braunkohlekraftwerk. GSF-Bericht-617 (1980).
- C6 Clarke, R.H. A model for short and medium range dispersion of radionuclides released to the atmosphere. NRPB-R91 (1979).
- C7 Culot, M.V., H.G. Olson and K.J. Schiager. Radon progeny control in buildings. COO-22731 (1973).
- C8 Castrén, O., M. Asikainen, M. Annanmäki et al. High natural radioactivity of bored wells as a radiation hygienic problem in Finland. p. 1033-1036 in: *IVth International Congress of IRPA. Proceedings*. (1977).
- D1 Denson, N.M. Uranium in coal in the western United States. U.S. Geological Survey Bulletin 1055. U.S. Geological Survey, Washington, D.C., 1959.
- D2 Davis, W. Jr., F.F. Haywood, J.L. Danek et al. Potential radiological impacts of recovery of uranium from wet-process phosphoric acid. ORNL/EPA-2 (1979).
- D3 Delcon, A. and M. Lazarevic. Possibilities for recovery of uranium as a by-product in the production of phosphate fertilizers and tripolyphosphate. p. 351-361 in: *The Recovery of Uranium*. IAEA, Vienna, 1971.
- D4 Den Boer, A.M. Electrical and electronic equipment containing radioactive substances. Seminar on the problems posed by the growing use of common goods containing radioactive substances. CEC report 3488/75 (1975).
- D5 Drichko, V.F., E.P. Lisachenko, O.A. Mihailova et al. Plants intake of some radionuclides from soils. USSR State Committee for the Use of Atomic Energy. (in Russian) (1976).
- E1 Eisenbud, M. and H.G. Petrow. Radioactivity in the atmospheric effluents of power plants that use fossil fuels. *Science* 144: 288-289 (1964).
- E2 English, R.A., J.V. Bailey and R.D. Brown. Application of Apollo cosmic radiation dosimetry to lunar colonization studies. p. 79-89 in: *Natural Radiation Environment II*. CONF-720805-P1 (1975).
- F1 Furr, A.K., T.F. Parkinson, R.A. Hinrichs et al. National survey of elements and radioactivity in fly ashes. Absorption of elements by cabbage grown in fly ash-soil mixtures. *Environ. Sci. Technol.* 11: 1194-1201 (1977).
- F2 Farmer, B.M., C.E. Styron, C.A. Phillips et al. The assessment of the radiological impact of western coal utilization, Phase 1. Monsanto Research Corporation, Mound Laboratory report. (1977).
- F3 Food and Agriculture Organization of the United Nations. *Fertilizer Handbook* (1978).
- F4 Fitzgerald, J.E., Jr. and E.L. Sensintaffar. Radiation exposure from construction materials utilizing byproduct gypsum from phosphate mining. p. 351-368 in: *Radioactivity in Consumer Products*. NUREG/CP-0001 (1978).
- F5 Federal Power Commission. Steam-electric plant air and water control data for the year ending December 31, 1972. Federal Power Commission report FPC-246. Washington, D.C. (1975).
- F6 Fisher, G.L., B.A. Prentice, D. Silberman et al. Physical and morphological studies of size-classified coal fly ash. *Environ. Sci. Technol.* 12: 447-451 (1978).
- F7 Furr, A.K., W.C. Kelly, C.A. Bache et al. Multielement uptake by vegetables and millet grown in pots on fly ash amended soil. *J. Agric. Food Chem.* 24: 885-888 (1976).
- G1 Gesell, T.F. and H.M. Prichard. The technologically enhanced natural radiation environment. *Health Phys.* 28: 361-366 (1975).
- G2 Gluskoter, H.J., R.R. Ruch, W.G. Miller et al. Trace elements in coal: occurrence and distribution. Illinois State Geological Survey Circular 499 (1977).
- G3 Goldstein, N.P., K.H. Sun and L.J. Gonzales. Radioactivity in fly-ash from a coal-burning power plant. *Trans. Am. Nucl. Soc.* 14: 66 (1971).
- G4 Guimond, R.J. and S.T. Windham. Radioactivity distribution in phosphate products, by-products, effluents and wastes. ORP/CSD-75-3 (1975).
- G5 Guimond, R.J. The radiological aspects of fertilizer utilization. p. 380-393 in: *Radioactivity in Consumer Products*. NUREG/CP-0001 (1978).
- G6 Graschenko, S.M., V.F. Drichko, E.P. Lisachenko et al. Natural radionuclides in cultivated soils and phosphate fertilizers. Atomizdat, Moscow, 1976.
- G7 Guimond, R.J., Jr., W.H. Ellett, J.E. Fitzgerald, Jr., et al. Indoor radiation exposure due to radium-226 in Florida phosphate lands. EPA-520/4-78-013 (1979).

- G8 Guimond, R.J. and S.T. Windham. Radiological evaluation of structures constructed on phosphate-related land. p.1457-1475 in: *Natural Radiation Environment III. CONF-780422 (Vol.2)* (1980).
- G9 Grigoriev, Yu. G. Problems of space radiobiology. p. 9-16 in: *Problems of Radioecology and Biological Effects of Low Doses of Ionizing Radiation* (A.M. Kuzin, ed.). USSR Academy of Sciences. Sykryvkar, 1976.
- G10 Gówny Urząd Statystyczny. Rocznik Statystyczny 1979. Rok XXXIX. Warszawa.
- G11 Gutt, W. and P.J. Nixon. Use of waste materials in the construction industry. Analysis of the RILEM Symposium by Correspondence. Building Research Establishment reprint R2/79 (1979).
- G12 Goldman, M. and S.S. Yaniv. Naturally occurring radioactivity in ophthalmic glass. p.227-240 in: *Radioactivity in Consumer Products. NUREG/CP-0001* (1978).
- H1 Hamilton, E.I. The relative radioactivity of building materials. *Am. Ind. Hyg. Assoc. J.* 32: 398-403 (1972).
- H2 Hsu, P.C., and P.S. Weng. Radiation exposure during air and ground transportation. *Health Phys.* 31: 522-524 (1976).
- H3 Hamilton, E.I. The chemical elements and human morbidity—water, air and places—a study of natural variability. *Sci. Total Environ.* 3: 3-85 (1974).
- H4 Halbritter, G., K.R. Bräutigam, F.W. Fluck et al. Contribution to a comparative environmental impact assessment of the use of coal and nuclear energy for electricity generation for selected site conditions in the FRG. p. 229-247 in: *Health Impacts of Different Sources of Energy. IAEA, Vienna, 1982.*
- I1 Ilyin, L.A., V.A. Knizhnikov, R.M. Barkhudarov et al. Population doses from natural radionuclides due to certain aspects of human activity. p. 1446-1456 in: *Natural Radiation Environment III. CONF-780422 (Vol.2)* (1980).
- I2 International Civil Aviation Organization. Annual report of the Council (1978).
- I3 International Commission on Radiological Protection. A report of the ICRP Task Group on the Biological Effects of High-energy Radiations. Radiobiological aspects of the supersonic transport. *Health Phys.* 12: 209-226 (1966).
- I4 International Atomic Energy Agency. Radiation protection standards for radioluminous timepieces. IAEA, Vienna, 1967.
- I5 Ilyin, L.A., V.A. Knizhnikov and R.M. Barkhudarov. A relative risk estimation of excessive frequency of malignant tumors in population due to discharges into the atmosphere from fossil-fuel and nuclear power stations. p. 189-193 in: *IVth International Congress of IRPA. Proceedings.* (1977).
- I6 International Commission on Radiological Protection. Limits for intakes of radionuclides by workers. ICRP Publication 30. *Annals of the ICRP.* Pergamon Press (1979-1982).
- J1 Jaworowski, Z., J. Bilkiewicz and E. Zylica. ²²⁶Ra in contemporary and fossil snow. *Health Phys.* 20: 449-450 (1971).
- J2 Jaworowski, Z. and D. Grybowska. Natural radionuclides in industrial and rural soils. *Sci. Total Environ.* 7: 45-52 (1977).
- J3 Jordan, S. and W. Schikarski. Evaluation of radioactive and non-radioactive trace constituents emitted from fossil-fuel and nuclear power plants. p. 525-535 in: *Environmental Behaviour of Radionuclides Released in the Nuclear Industry. IAEA, Vienna, 1973.*
- J4 Jaworowski, Z. Communication (1980).
- J5 Jaworowski, Z., J. Bilkiewicz, L. Kownacka et al. Artificial sources of natural radionuclides in environment. p. 809-818 in: *The Natural Radiation Environment II. CONF-720805-P2* (1972).
- J6 Johnson, J.E. Smoke detection containing radioactive materials. p. 434-440 in: *Radioactivity in Consumer Products. NUREG/CP-0001* (1978).
- J7 Jacobi, W. Umweltradioaktivität und Strahlenexposition durch radioaktive Emissionen von Kohlekraftwerken. *GSF-Bericht S-760* (1981).
- J8 Jacobi, W., H. Schmier and J. Schwibach. Comparison of radiation exposure from coal-fired and nuclear power plants in the Federal Republic of Germany. p. 215-227 in: *Health Impacts of Different Sources of Energy. IAEA, Vienna, 1982.*
- J9 Johnson, R.H. Jr., D.E. Bernhardt, N.S. Nelson et al. Assessment of potential radiological health effects from radon in natural gas. EPA-520/1-73-004 (1973).
- K1 Kaakinen, J.W., R.M. Jorden, M.H. Lawasani et al. Trace element behaviour in coal-fired power plant. *Environ. Sci. Technol.* 9: 862-869 (1975).
- K2 Klein, D.H., A.W. Andren, J.A. Carter et al. Pathways of thirty-seven trace elements through coal-fired power plant. *Environ. Sci. Technol.* 9: 973-979 (1975).
- K3 Keyser, T.R., D.F.S. Natusch, C.A. Evans, Jr., et al. Characterizing the surface of environmental particles. *Environ. Sci. Technol.* 12:768-773 (1978).
- K4 Kirchmann, R., R. Boulenger, J. Colard et al. Evaluation de la dose à l'homme résultant de la présence de radionuclides naturels dans les engrais phosphatés d'origine minérale. p. 1045-1048 in: *IVth International Congress of IRPA. Proceedings.* (1977).
- K5 Kirchmann, R., M. Darcheville and G. Koch. Accumulation of radium-226 from phosphate fertilizers in cultivated soils and transfer to crops. p. 1667-1672 in: *Natural Radiation Environment III. CONF-780422 (Vol.2)* (1980).
- K6 Krisiuk, E.M., E.P. Lisachenko, S.I. Tarasov et al. Exposures from radiation sources of natural origin. p.870-881 in: *Proceedings of the Third International Congress of the International Radiation Protection Association. CONF-730907-P2* (1974).
- K7 Kolb, W. and H. Schmier. Building material induced radiation exposure of the population. Presented at the Third European Congress of the International Radiation Protection Association. Amsterdam, May 1975.
- K8 Krisiuk, E.M., S.I. Tarasov, V.P. Shamov et al. A study on radioactivity of building materials. Leningrad Research Institute for Hygiene, 1971.
- K9 Krejci, K. and A. Zeller. Public health aspects of production and application of radioluminous materials activated with tritium and carbon-14. p. 285-293 in: *Radioactivity in Consumer Products. NUREG/CP-0001* (1978).
- K10 Kossel, F. Strahlenbelastung und Strahlenschutz bei der Verwendung von Fernsehgeräten. in: *Gemeinsamer Kongress der Deutschen und der Österreichischen Röntgengesellschaft*, 1973.
- K11 Knizhnikov, V.A. and R.M. Barkhudarov. The comparative estimate of radioactive hazard for the population from effluents of thermoelectric power stations and atomic electric power stations into the atmosphere. *Atomic Energy* 43: 3 (1977).
- K12 Kirchmann, R., E. Bonnyns, J. Colard et al. Teneurs en radionucléides naturels des phosphates bruts d'engrais phosphatés utilisés en Belgique. p. 227-241 in: *Seminar on the radiological burden of man from natural radioactivity in the countries of the European Communities. CEC report V/2408/80* (1980).
- L1 Linton, R.W., A. Loh and D.F.S. Natusch. Surface predominance of trace elements in airborne particles. *Science* 191: 852-854 (1976).
- L2 Lee, H., T.O. Peyton, R.V. Steele et al. Potential radioactive pollutants resulting from expanded energy programs. EPA-600/7-77-082 (1977).
- L3 Lindeken, C.L. and D.G. Coles. The radium-226 content of agricultural gypsums. p. 369-375 in: *Radioactivity in Consumer Products. NUREG/CP-0001* (1978).
- L4 Lisachenko, E.P. and O.L. Obuhova. The radioactivity of coals, ashes and slags in the USSR. Presented at the 2nd Special Symposium on the Natural Radiation Environment. Bombay, 1981 (Proceedings in print).
- L5 Letourneau, E.G., R.G. McGregor and H. Taniguchi. Background levels of radon and radon daughters in Canadian homes. Paper presented at the Nuclear

- Energy Agency (NEA) Meeting on Personal Dosimetry and Area Monitoring Suitable for Radon and Daughter Products. Paris, November 1978.
- M1 Mastinu, G.G. Natural radioactivity levels in releases from coal-fired power plants in Italy. p. 429-436 in: Seminar on the radiological burden of man from natural radioactivity in the countries of the European Communities. CEC report V/2408/80 (1980).
- M2 Martin, J.E., E.D. Harvard, D.T. Oakley et al. Radioactivity from fossil-fuel and nuclear plants. p. 325-337 in: Environmental Aspects of Nuclear Power Stations. IAEA, Vienna, 1971.
- M3 McBride, J.P., R.E. Moore, J.P. Witherspoon et al. Radiological impact of airborne effluents of coal-fired and nuclear power plants. ORNL-5315 (1977).
- M4 Mills, W.A., R.J. Guimond and S.T. Windham. Radiation exposures in the Florida phosphate industry. p. 1049-1052 in: IVth International Congress of IRPA. Proceedings. (1977).
- M5 Menzel, R.G. Uranium, radium and thorium content in phosphate rocks and their possible radiation hazard. J. Agric. Good Chem. 16: 231-234 (1968).
- M6 Meikle, P.G. Fly-ash. Chapter V in: Solid Waste. (C.L. Mantell, ed.). John Wiley, New York, 1975.
- M7 Mjõnes, L. Measurements of gamma radiation in Swedish houses by means of mailed CaSO₄/Dy dosimeters. p. 1077-1089 in: Natural Radiation Environment III. CONF-780422 (Vol.2) (1980).
- M8 Moghissi, A.A., M.W. Carter, R.E. Simpson et al. Evaluation of public health implications of radioluminous materials. p. 256-276 in: Radioactivity in Consumer Products. NUREG/CP-0001 (1978).
- M9 Moghissi, A.A. and M.W. Carter. Public health implications of radioluminous materials. DHEW (FDA)76-8001 (1975).
- M10 McBride and B.E. Ruscoe. The value of a fire detector in the home. Fire study No. 9. National Research Council of Canada (1962).
- M11 McMillan, R.C. and S.A. Horne. Eye exposure from thoriated optical glass. p. 882-888 in: Proceedings of the Third International Congress of the International Radiological Protection Association. CONF-730907-P2 (1974).
- M12 Mishra, U.C., B.Y. Lalit and T.V. Ramachandran. Radioactivity release to the environment by thermal power stations using coal as a fuel. Sci. Total Environ. 14: 77-83 (1980).
- M13 Mastinu, G.G. The radiological impact of geothermal energy. p. 437-445 in: Seminar on the radiological burden of man from natural radioactivity in the countries of the European Communities. CEC report V/2408/80 (1980).
- M14 McGregor, R.G. and H. Taniguchi. Radiation survey of Long Harbour, Newfoundland. Appendix F (p. 117-137) of final report entitled Task Force on Fluoride. Canadian Public Health Association, Long Harbour, Newfoundland (1978).
- N1 Nishiwaki, Y., Y. Tsunetoshi, T. Shimizu et al. Atmosphere contamination of industrial areas including fossil-fuel power stations, and a method of evaluating possible effects on inhabitants. p. 247-278 in: Environmental Aspects of Nuclear Power Stations. IAEA, Vienna, 1971.
- N2 Natusch, D.F.S., J.R. Wallace and C.A. Evans, Jr. Toxic trace elements: preferential concentration in respirable particles. Science 183: 202-204 (1974).
- N3 National Council on Radiation Protection and Measurements. Radiation exposure from consumer products and miscellaneous sources. NCRP report No. 56 (1977).
- N4 National Plant Food Institute. The fertilizer handbook. Washington, D.C., 1963.
- N5 Nuclear Energy Agency of the OECD. Exposure to radiation from the natural radioactivity of building materials. Report by a Group of Experts of the OECD/NEA (1979).
- N6 Niemeyer, R.G., F.N. Case and N.H. Cutshall. Evaluation of polonium-210 static eliminators. p. 423-433 in: Radioactivity in Consumer Products. NUREG/CP-0001 (1978).
- O1 Ondov, J.M., R.C. Ragaini and A.H. Biermann. Elemental particle-size emissions from coal-fired power plants: use of an inertial cascade impactor. Atmos. Environ. 12: 1175-1185 (1978).
- O2 O'Riordan, M.C., M.J. Duggan, W.B. Rose et al. The radiological implications of using by-product gypsum as a building material. NRPB-R7 (1972).
- O3 O'Riordan, M.C. and G.J. Hunt. Radiological controls for construction materials. p. 1053-1056 in: IVth International Congress of IRPA. Proceedings. (1977).
- O4 O'Brien, K. The cosmic ray field at ground level. p. 15-54 in: The Natural Radiation Environment II. CONF-720805-P1 (1975).
- O6 O'Riordan, M.C. and G.J. Hunt. Radioactive fluorescers in dental porcelains. NRPB-R25 (1974).
- O7 Optical Manufacturers Association. Ophthalmic Glass Radiological Standard. (1975).
- P1 Pensko, J. and Z. Stpiczynska. Measurements of natural radioactivity and emanation power of coal-fueled power plant wastes used in building industry. p. 793-800 in: IVth International Congress of IRPA. Proceedings. (1977).
- P2 Polgar, E. and I. Kurcz-Cziky. Natural and artificial radioactivity of fallout in Hungary. Communication (1970).
- P3 Parungo, F., E. Ackerman, H. Proulx et al. Nucleation properties of fly-ash in a coal-fired power plant plume. Atmos. Environ. 12: 929-935 (1978).
- P4 Partridge, J.E., T.R. Horton, E.L. Sensintaffar et al. Radiation dose estimates due to air particulate emissions from selected phosphate industry operations. ORP/EERF-78-1 (1978).
- P5 Prantl, F.A. Radiation survey of Long Harbour, Newfoundland. Communication. (1979).
- P6 Pfister, H., G. Philipp and H. Pauly. Population dose from natural radionuclides in phosphate fertilizers. Rad. and Environm. Biophys. 13: 147-261 (1976).
- P7 Pfister, H. and H. Pauly. External radiation exposure due to natural radionuclides in phosphate fertilizers in the Federal Republic of Germany. p. 447-467 in: Seminar on the radiological burden of man from natural radioactivity in the countries of the European Communities. CEC report V/2408/80 (1980).
- P8 Pellerin, P. Communication (1982).
- R1 Ray, S.S. and F.G. Parker. Characterization of ash from coal-fired power plants. EPA-600/7-77-010 (1977).
- R2 Ross, R.C. Uranium recovery from phosphoric acid nears reality as a commercial uranium source. Eng. Min. J. 176: 80 (1975).
- R3 Ring, R.J. Manufacture of phosphatic fertilizers and recovery of by-product uranium. A review. AAEC/E-355 (1975).
- R4 Roessler, C.E., Z.A. Smith, W.E. Bolch et al. Uranium and radium-226 in Florida phosphate materials. Health Phys. 37: 269-277 (1979).
- R5 Reid, D.F., W.M. Sackett and R.F. Spalding. Uranium and radium in livestock feed supplements. Health Phys. 32: 535-540 (1977).
- R6 Roessler, C.E., R. Kautz, W.E. Bolch, Jr., et al. The effect of mining and land reclamation on the radiological characteristics of the terrestrial environment of Florida's phosphate regions. p. 1476-1493 in: Natural Radiation Environment III. CONF-780422 (Vol.2) (1980).
- R7 Radke, G. Solar flare dose rates in a near earth polar orbit. in: The Current Experimental Approach to the Radiobiological Problems of Space Flight (J.F. Janni and R.E. Holly, eds.) Aerosp. Med. 40: 1495-1503 (1969).
- R8 Ristagno, C.V. The use of tritium luminous sources for lighting digital wristwatches. p. 320-322 in: Radioactivity in Consumer Products. NUREG/CP-0001 (1978).
- R9 Rundo, J., F. Markun and N.J. Plondke. Observation of high concentrations of radon in certain houses. Health Phys. 36: 729-730 (1979).

- S1 Schmier, H. Communication (1977).
- S2 Styron, C.E. An assessment of natural radionuclides in the coal-fuel cycle. p. 1511-1520 in: *Natural Environment III. CONF-780422 (Vol.2)* (1980).
- S3 Swanson, V.E., J.H. Medlin, J.R. Hatch et al. Collection, analysis, and evaluation of coal samples in 1975. U.S. Department of Interior. Geological Survey report 76-468 (1976).
- S4 Steininger, E. Utilization of by-products from the wet phosphoric acid production to prevent environmental pollution. Expert group meeting on minimizing pollution from fertilizer plants. Helsinki, Finland, 1974.
- S5 Stieve, F.E. Communication (1976).
- S6 Swedjemark, G.A. and N. Hagberg. Communication (1976).
- S7 Spurgeon, D. Eldorado radiates hope. *Nature* 260: 278 (1976).
- S8 Savun, O.I, I.N. Senchuro, P.I. Shavrin et al. Distribution of radiation dose in the radiation belts of the earth in the year of maximum solar activity. *Kosm. Issled* 11(1): 119-123 No. 1 (1973).
- S9 Stieve, F.E. and H. Schmier. Radioaktive Substanzen in Baustoffen. in: *Seminar on the problems posed by the growing use of common goods containing radioactive substances*. CEC report 3488/75 (1975).
- S10 Smith, R. Radioactive choppers. EPA confirms high dose rates from false teeth. *Nucleonics Week*, April, 1976.
- S11 Stinespring, C.D. and G.W. Stewart. Surface enrichment of aluminosilicate minerals and coal combustion ash particles. *Atmos. Environ.* 15: 307-313 (1981).
- S12 Smith, R.D., J.A. Campbell and K.K. Nelson. Characterization and formation of submicron particles in coal-fired plants. *Atmos. Environ.* 13: 607-617 (1979).
- S13 Swedjemark, G.A. Radioactivity in houses built of aerated concrete based on alum shale. *SSI:1980-14* (1980).
- S14 Swedjemark, G.A., B. Hakansson and N. Hagberg. Radiation levels in houses built on waste tailings piles from the mining and treatment of alum shale. *SSI:1979-006* (1979).
- S15 Schmier, H. Neuerliche Stellungnahme zur Frage der Verwendung von Uran für das Einfärben von Zahnmassen.
- S16 Schmier, H. Uran in keramischen Gegenständen. *STH-Bericht* 12/1981 (1981).
- S17 Sairensi, E., K. Moriwaki, M. Shimizu et al. Estimation of radiation dose from porcelain teeth containing uranium compound. *J. Dent. Res.* 59: 1136-1140 (1980).
- S18 Sairensi, E., K. Moriwaki, M. Shimizu et al. Determination of uranium content in dental porcelains by means of the fission track method and estimation of radiation dose to oral mucosa by radioactive elements. *Health Phys.* 38: 483-492 (1980).
- S19 Schmier, H. Strahlenexposition durch Kern- und Kohlekraftwerke. p.115-120 in: *Umweltrisiko 80*. Georg Thieme Verlag, Stuttgart, 1981.
- T1 Taylor, F.E. and G.A.M. Webb. Radiation exposure of the U.K. population. *NRPB-R77* (1978).
- T2 Tomczyńska, J., K. Błaton-Albicka, J. Peńsko et al. The results of measurements of the natural radionuclides in coal power plants wastes and light concrete samples. For publication in *Nukleonika*, Warsaw, 1981.
- T3 Tracy, B.L. and F.A. Prantl. Radiological implications of thermal power production. p. 185-193 in: *Health Impacts of Different Sources of Energy*. IAEA, Vienna, 1982.
- U1 United Nations. 1978 Statistical Yearbook. New York, 1979.
- U2 United Nations. Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation 1977 report to the General Assembly, with annexes. United Nations publication (Sales No. E.77.IX.1). New York, 1977.
- U3 United States Department of Interior. Mineral facts and problems. Bureau of Mines Bulletin 667. Washington, D.C., 1976.
- U4 United States Congress. Joint Committee on Atomic Energy. Use of uranium mill tailings for construction purposes. Washington, 1971.
- U5 United Nations. 1979 Yearbook of World Energy Statistics. New York, 1981.
- U6 United Nations. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, with annexes. Volume I: Levels; Volume II: Effects. United Nations publication (Sales Nos. E.72.IX.17 and 18). New York, 1972.
- V1 Vine, J.D. Uranium bearing coal in the United States. U.S. Geological Survey professional paper prepared for the International Conference on Peaceful Uses of Atomic Energy. Geneva, 1955.
- V2 Vine, J.D. Geology of uranium in coaly carbonaceous rocks. U.S. Geological survey (1962).
- W1 Wachsmann, F. and D.F. Regulla. Exposure of aircraft passengers to radiation from transported radioactive goods. *Kerntechnik* 20: 318-322 (1978).
- W2 Wallace, R. Measurements of the cosmic radiation dose in subsonic commercial aircraft compared to the city-pair dose calculation. *LBL-1505* (1975).
- W3 Wehner, R. Legal and practical aspects of radioactivity in consumer products in the Federal Republic of Germany. p. 97-105 in: *Radioactivity in Consumer Products*. NUREG/CP-0001 (1978).
- W4 Wilkins, B.T. and D.W. Dixon. The radiological testing of consumer products: 1976-78. *NRPB-R85* (1979).
- W5 Webb, G.A.M., B.T. Wilkins and A.D. Wrixon. Assessment of the hazard to the public from antistatic brushes containing polonium-210 in the form of ceramic microspheres. *NRPB-R36* (1975).
- W6 Wilson, R. Computer analysis of data on fire detectors available for purchase in Massachusetts. For: *Fire Prevention, Fire Protection Board*, 1976.
- W7 Wrixon, A.D. and G.A.M. Webb. Miscellaneous sources of ionizing radiation in the United Kingdom: the basis of safety assessments and the calculation of population dose. p. 577-593 in: *Population Dose and Standards for Man and His Environment*. IAEA, Vienna, 1974.
- W8 Wang, Y.S. Measurement of ionizing radiation from colour television receivers by thermoluminescent dosimeters. *Health Phys.* 28: 78-80 (1975).
- W9 Wardaszko, T. Radiation hazard to population due to radon-222 in natural gas. *Postepy Fiz. Med. Warsaw* (1979).
- W10 Watanabe, A., E.J. Lutz and A.A. Moghissi. Atmospheric releases from fossil fuel power plants in the United States. *Environ. Int.* 4: 357-382 (1980).
- Z1 Zuk, W.M., A. Armstrong and G.C. Jack. Radiation sources in Ottawa area secondary schools. Report IR-107. Health and Welfare Canada, 1973.