SOURCES AND EFFECTS OF IONIZING RADIATION

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NOTE

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ANNEX A

Exposures from natural sources of radiation

CONTENTS

INTRODUCTION

1. Natural ionizing radiation arises in outer space, where cosmic rays are formed, and in and on the earth, where radionuclides normally present in soil, air, water, food and the body undergo radioactive decay. Penetrating radiations and radioactive materials pervade the natural environment. The main types of radiation are gamma rays, alpha and beta particles, neutrons and muons. Human exposure occurs by irradiation from sources outside the body (external exposure) and upon the decay of radionuclides taken into the body through ingestion and inhalation (internal exposure). The assessment of radiation doses in humans from natural sources is important because natural ionizing radiation is the largest contributor to the collective effective dose received by the world's population. In this Annex, the expressions "natural radiation" and "natural radiation background" are often used to refer to "natural sources of ionizing radiation".

2. Some of the contributions to the total exposure from the natural radiation background are quite constant in space and time and practically independent of human practices and activities. This is true, for example, of the doses received from the ingestion of ^{40}K, a long-lived radioisotope of an element that is homeostatically controlled, and also of doses from the inhalation and ingestion of cosmogenic radionuclides, which are relatively homogeneously distributed at the surface of the globe.

3. Other contributions depend strongly on human activities and practices and are therefore widely variable. In particular, the doses from indoor inhalation of short-lived decay products of radon gas are influenced by local geology and by building design, as well as by the choice of building materials and of ventilation systems. Also, concentrations of the short-lived decay products are, as a rule, higher indoors than outdoors. Therefore, people who reside somewhat above the ground surface in apartment blocks or who mostly stay outdoors in the open air are likely to incur far less exposure to radon than those who occupy single dwellings or who spend most of their time in enclosed spaces.

4. Intermediate types of exposure are those that are neither widely variable nor relatively constant at the surface of the globe. Examples are (a) external doses from cosmic rays, which vary with altitude and, to a much lesser extent, with latitude, and (b) external doses from radiation of terrestrial origin (that is, the radionuclides present in the crust of the earth and in building materials), which are affected by location and accommodation.

5. Doses from the inhalation of radon in dwellings are much greater than those from all other components of natural radiation. The main cause of high concentrations of radon in dwellings is the influx of the gas from the subjacent earth; high doses are caused by geological circumstances modified by the manner in which a dwelling is built and used. Since increasing attention is being devoted worldwide to both the radiological and the epidemiological aspects of this topic, considerable emphasis is placed in this Annex on exposure to radon and its decay products in air.

6. Since the publication of the UNSCEAR 1988 Report [U1], further information on radiation exposures from natural sources, especially with regard to radon and its short-lived decay products, has become available. This Annex updates the evaluation of exposures presented in the UNSCEAR 1988 Report [U1]. The additions and modifications present a broader view of average radiation exposures worldwide and of the range of levels experienced in particular locations. The procedures for estimating the tissue doses from inhalation of radon short-lived decay products are under continuing review and the International Commission on Radiological Protection (ICRP) has assigned new radiation- and tissue-weighting factors to define the effective dose [16]. Despite these changes, the overall assessment of dose from natural sources of radiation is similar.

7. Radiation exposures from extra-terrestrial sources (cosmic rays and cosmogenic radionuclides) and from terrestrial sources (^{40}K, ^{87}Rb and radionuclides of the uranium and thorium series) may be said to form the basic natural radiation background because of the relative constancy of exposure. These exposures are discussed in Chapters I and II in this Annex. Among the terrestrial radionuclides, the radon isotopes in the uranium and thorium decay series play an important role because of the magnitude of the doses they deliver and because of the variability of those doses. The radon isotopes are given special consideration in Chapter III. Exposures related to the extraction and processing of earth materials are considered in Chapter IV, with the exception of the extraction and processing of uranium, which is part of the nuclear fuel cycle and is dealt with in Annex B, "Exposures from man-made sources of radiation".

8. The exposures assessed in this Annex are those to members of the public. They include the exposures outdoors and indoors in normal circumstances both at home and at work. The additional exposures that people receive at work because they are exposed to man-made radiation sources or to elevated levels of natural radiation caused by their work are discussed in Annex D, "Occupational radiation exposures".

I. COSMIC RADIATION

A. COSMIC RAYS

1. The radiation environment

9. Space is permeated by ionizing radiation. The radiation consists of various charged particles of various origins and energies. All are of concern in space travel, and some by creating secondary particles, lead to human exposure during air travel and on earth, with decreasing intensity from the highest altitudes down to sea level. In this Chapter, emphasis is placed on the everyday circumstances of exposure, and brief reference is made to exposure in space.

10. Radiations in space may be classified according to origin as trapped particle radiation, galactic cosmic radiation or solar particle radiation [A1, C1, F1, N1, S1]. Trapped radiation consists mainly of electrons and protons held in orbits around the earth by its magnetic field. Galactic cosmic radiation consists mainly of protons with some helium and heavier ions. Solar particle radiation has similar composition. These three classes are described in turn.

11. Trapped protons and electrons are in two zones or radiation belts, one within and one outside of 2.8 earth radii at the equator, with greater intensities and energies in the outer zone. There are appreciable temporal variations in intensities; energies of electrons reach several megaelectronvolts (MeV) and energies of protons reach a few hundred MeV. Trapped protons are more important than electrons for manned missions in low earth orbit. Although particles trapped in radiation belts can present a radiation hazard for space travellers, they do not result in any radiation dose at ground level.

12. Galactic cosmic rays are created outside the solar system; they are generally believed to be produced and accelerated as a consequence of stellar flares, supernova explosions, pulsar acceleration or the explosion of galactic nuclei [O9]. There is, however, no generally accepted theory of their generation and acceleration. Cosmic rays in our galaxy have a mean residence time of about 200 million years, being contained by the magnetic field of interstellar space [O9]. Energies of the cosmic-ray particles are mostly between 10^2 and 10^5 MeV, but they can reach much higher values [S1]. The spectrum is affected by changes in the magnetic fields within the solar system, caused by solar activity, with maximum intensity at periods of low activity and vice versa. Of the heavy ions, called HZE particles (high atomic number and energy), that are components of the cosmic-ray flux, iron is the most significant for exposure because of its relative abundance and high atomic number [L1]. Galactic cosmic rays are also affected by the geomagnetic field near the earth, which prevents some

particles from reaching the atmosphere but is progressively less effective in doing so from the geomagnetic equator to the poles. This class of space radiation is the most significant for exposure on earth and in aircraft.

13. When the primary particles from space, mainly protons, enter the atmosphere, those with high energy interact with nuclei present in the air (nitrogen, oxygen, argon) to produce neutrons, protons, muons, pions and kaons, in addition to a variety of reaction products, some of the more important of which, from the dosimetric point of view, are ^{3}H, ^{7}Be and ^{22}Na. These high-energy reactions are called spallation reactions. Many of the secondary particles have sufficient energy to initiate whole sequences of further nuclear reactions with nuclei present in the air. A cascade process is the result [I2]. The properties of some of the more important cosmic-ray particles are listed in Table 1 [E6, U5].

14. The nucleonic components, protons and neutrons, are mainly produced in the upper layers of the atmosphere. The protons are formed mainly in spallation reactions, while neutrons are produced both by spallation reactions and by the so-called evaporation of neutrons due to low-energy (p,n) reactions. Neutrons lose energy by elastic collisions and, when thermalized, are captured by ^{14}N to form ^{14}C. Because nucleons rapidly lose energy through ionization and nuclear collisions, the nucleonic flux density is considerably attenuated in the lower part of the atmosphere and accounts only for a few per cent of the dose rate at sea level [U5]. The neutron spectrum covers a wide energy range in the lower atmosphere, from thermal to 100 MeV and more, but the high-energy neutrons are most significant because of their high fluence to equivalent dose conversion coefficients.

15. Pions and kaons have short lives and essentially decay in the atmosphere before reaching ground level. The electromagnetic cascade is initiated from photons produced in the decay of neutral pions. These photons create electron-positron pairs and Compton electrons, which in turn produce additional photons by bremsstrahlung and positron-electron annihilation. As the number of shower particles increases, their average energy decreases. Finally, the majority of electrons will drop to energies where collision losses dominate and the cascade will die out [I2]. Except in the lower layers of the atmosphere, electrons are main sources of ionization [U5]. On the other hand, muons, which have a small cross-section for interaction with atomic nuclei and a mean life of 2.2 μs before decay, penetrate into the lower layers of the atmosphere and are the main constituent of cosmic rays at sea level [U5]. Most muons occur in the energy range 0.2-20 GeV, with a median value of 2 GeV [N2].

16. Solar particle radiation, as the name implies, comes from the sun. Particles of very low energy are generated continuously, but more energetic particles are emitted more copiously during magnetic disturbances. Large emissions associated with flares, called solar particle events, occur occasionally during the active period of the 11-year solar cycle [H1]. Energies are usually between 1 and 100 MeV but can be an order of magnitude higher. Such events are important in low earth orbit, but anomalously large solar particle events, which occur about once a decade, may be of vital importance for manned missions beyond the magnetosphere. Although the fluence rate of solar particles over several years exceeds the fluence rate of galactic particles, solar particles are less significant for radiation exposure in the atmosphere, because most have insufficient energy to penetrate the earth's magnetic field. The emission of solar particle radiation follows the 11-year solar cycle, reaching a maximum during increased solar activity and a minimum during the period of the quiet sun. Because the less energetic galactic cosmic-ray particles are deflected away from the solar system by the magnetic irregularities transported by the solar particle radiation, an 11-year modulation of the galactic cosmic-ray flux density at the earth is produced, the cosmic-ray flux density being lowest during times of maximum solar activity and vice versa (Figure I).

2. Factors affecting dose

17. To estimate human doses from cosmic rays, it is necessary to consider the effects of altitude, latitude and shielding.

(a) Altitude

18. The absorbed dose rates in air from the directly ionizing and indirectly ionizing (neutron) components of cosmic ray are shown in Figure I as a function of altitude at a geomagnetic latitude of 50° N. These results are based on numerous measurements on the ground and aboard aircraft, which were compiled in the UNSCEAR 1977 Report [U4]. During periods of maximum solar activity, dose rates of the ionizing component are reduced about 10% at 10 km altitude and to a lesser degree at sea level.

19. The dose rates from neutrons, the dominant indirectly ionizing component, are much less than those due to the ionizing component, but they increase more rapidly with altitude, peaking at 10-20 km. The variations during the solar cycle are greater, with decreases in the dose rates of a few tens of per cent at an altitude of 10 km during solar maxima and to a lesser degree at sea level.

20. The values of the production rate of cosmic ray ions at sea level reported after 1960 for mid- and

high-latitudes show relatively good agreement, with a cluster of values around 2.1 cm^{-3} s^{-1} and extremes at 1.9 and 2.6 cm^{-3} s^{-1} [U3]. Since 1977, the Committee has consistently adopted a value of 2.1 cm^{-3} s^{-1} for the purposes of computing the absorbed dose rate from the directly ionizing component. Assuming that each ion pair in moist air requires 33.7 eV to be produced, the absorbed dose rate in air is 32 nGy h^{-1} at sea level at mid- and high-latitudes. Since the dose is delivered mainly by muons, for which the radiation weighting factor is unity [I6], this numerical value may also be taken for the equivalent dose rate in the open.

21. The cosmic-ray neutron flux density at sea level is small and difficult to measure, mainly because the neutron energy spectrum extends over a very wide range, from fractions of eV to tens of GeV. At 50° N latitude, the neutron flux density is about 0.008 cm^{-2} s^{-1} at sea level [H2, H12]. A range of estimates of equivalent dose rates from 1.4 to 3.3 nSv h^{-1} were reported in the UNSCEAR 1988 Report [U1] for different computational geometries and exposures. The lowest values are found for low latitudes (24° N) [N23], suggesting the presence of a substantial latitude effect, even at sea level. In the UNSCEAR 1988 Report, the average effective dose equivalent rate was taken to be 2.4 nSv h^{-1}. Changes to the radiation-weighting factor were recommended by the ICRP in 1991 [I6]. Considering the neutron energy spectrum, those changes lead to an increase of about 50% of the effective dose rate from neutrons [H20]. The average effective dose rate from cosmic-ray neutrons at sea level is, therefore, estimated to be 3.6 nSv h^{-1}.

(b) Latitude

22. Lower-energy charged particles are deflected back into space by the earth's magnetic field. This effect is latitude-dependent, so that a greater flux of low-energy protons reaches the top of the atmosphere at the poles than in equatorial regions. Thus, the ionization produced in the atmosphere is also latitude-dependent. This latitude effect increases with altitude; at sea level, the cosmic-ray absorbed dose rate from the directly ionizing component gradually declines to 90% of its high-latitude value between 40° and the geomagnetic equator [T11]. For example, the cosmic-ray absorbed dose rate in air has been found to be 27-31 nGy h^{-1} at Hong Kong (latitude 22.3° N) [T11] and 28 nGy h^{-1} at Shenzen, China (latitude 22.6° N) [Y1]. These figures are to be compared to the value of 32 nGy h^{-1} observed at high- and mid-latitudes.

(c) Shielding

23. Ordinary buildings such as houses and offices provide some shielding against the directly ionizing component of cosmic rays, but data are still scarce; the magnitude of the effect depends on the structure and composition of the buildings. Limited measurements and calculations, summarized in the UNSCEAR 1988 Report [U1] and elsewhere [N2], give shielding factors from 0.96 for small wooden houses to 0.42 for substantial concrete buildings. Calculations for muons yield dose reductions ranging from 10% to 30% compared to the value in a reference room, when the parameters affecting exposure (size of building, thickness of structural elements, proximity to other buildings) are varied within reason [F2]. Without more information on shielding and on the nature of buildings, the same universal shielding factor of 0.8 is retained as before [U1]. It is recognized, however, that there may be 25% uncertainty associated with this value.

24. Information on the shielding effect of ordinary buildings on the neutrons in cosmic rays is more limited than for muons, although the broad spectrum must be affected to some degree, with virtually no attenuation by a shingle roof, for instance, and an order of magnitude attenuation by a substantial concrete element [N3]. In this Annex, no account has been taken of the shielding effect of the neutron component.

3. Exposures

(a) Ground level

25. With the conventional indoor occupancy factor of 0.8, that is, the fraction of time persons are deemed, on the average, to be indoors at home and at work [U1], the annual effective dose from the directly ionizing component of cosmic rays is estimated to be 240 μSv at sea level. Since the shielding effect is ignored for the neutron component of cosmic rays, an occupancy adjustment is not needed. The annual effective dose from the neutron component of cosmic rays is approximately 30 μSv at sea level. The uncertainty in this estimate is, clearly, appreciable.

26. To estimate the population-weighted annual effective dose from cosmic rays at ground-level, account needs to be taken of the variation of the effective dose rate with altitude and of the distribution of the world's population with altitude. Analytical expressions have been developed for the general relationship between annual dose and altitude for both the directly and indirectly ionizing components [B1]:

$$\dot{E}_I(z) = \dot{E}_I(0)[a_I \exp(-\alpha_I z) + b_I \exp(\beta_I z)] \quad (1)$$

where $\dot{E}_I$ is the effective dose rate in μSv a^{-1} for the directly ionizing component; $\dot{E}_I(0)$ is the reference value at sea level, 240 μSv a^{-1}; z is the altitude in km; $a_I = 0.21$; $\alpha_I = 1.6$ km^{-1}; $b_I = 0.80$; $\beta_I = 0.45$ km^{-1}.

$$\dot{E}_N(z) = \dot{E}_N(0)\exp(\alpha_N z) \quad (2)$$

$$\dot{E}_N(z) = \dot{E}_N(0)[b_N\exp(\beta_N z)] \quad (3)$$

with equation (2) applying for $z < 2$ km and equation (3) applying for $z > 2$ km, where $\dot{E}_N$ is the effective dose rate in μSv a^{-1} for the indirectly ionizing component from neutrons and $\dot{E}_N(0) = 30$ μSv a^{-1}; $\alpha_N = 1.0$ km^{-1}; $b_N = 2.0$; and $\beta_N = 0.70$ km^{-1}. These equations may be applied to estimate doses from cosmic rays at habitable elevations around the world. They include an allowance for shielding, as described above.

27. The distribution of the world population by altitude and urbanization has been analysed [B1], with some simplifying assumptions. When the foregoing equations are applied and the two components summed, the distribution of collective effective dose with altitude is obtained. The annual value of the average effective dose worldwide is estimated to be 380 μSv, with the directly ionizing and indirectly ionizing components contributing 300 μSv and 80 μSv, respectively. The global value of the collective effective dose is about $2\ 10^6$ man Sv, some 90% of which occurs in the northern hemisphere by virtue of the population distribution. Somewhat less than one fifth of the collective dose is attributable to China, when account is taken of both population and elevation [H13, N22].

28. Since human habitations are mostly at lower altitudes, about one half of the collective dose is received by the two thirds of the world population that lives below 0.5 km. The one fiftieth (approximately) of the population living above 3 km receives a disproportionate one tenth of the collective dose. Table 2 lists average annual doses from cosmic rays with the separate contributions of the directly and indirectly ionizing components indicated. In high altitude cities the increasing importance of neutrons with elevation is evident. There is considerable variability in total dose. The annual value in La Paz, for example, is five times the global average. In round terms, annual values of the effective dose from cosmic rays range from 270 to 2,000 μSv, with a population-weighted mean of 380 μSv.

(b) Air travel

29. Flight pattern and duration are the principal determinants of cosmic-ray doses to aircrew and passengers. Modern commercial aircraft have optimum operating altitudes near 13 km, but flight paths are assigned according to use and safety requirements, and adequate data do not seem to be available for flight patterns [W1]. In the UNSCEAR 1988 Report [U1], a representative operating altitude of 8 km was assumed, because of the predominance of short-travel flights, with an average speed of 600 km h^{-1}. Alternative assumptions are also made; for example, an altitude of 9 km and a speed of 650 km h^{-1} were used for an assessment in the United Kingdom [H3], and an altitude of 7 km is indicated for flights by United States carriers lasting less than an hour and 11 km for longer flights [O9]. Computational codes have been developed to allow calculating radiation levels throughout the atmosphere (see, e.g. [O9]), and additional measurement experience is being acquired (see, e.g. [N12, R8, S30]). For a given altitude, dose rates for flights over the poles are substantially greater than those for flights over equatorial regions.

30. An international digest of air traffic statistics is published routinely [I3]. Data for 1989 show that $1.8\ 10^{12}$ passenger-kilometres were flown in that year, which translates into $3\ 10^9$ passenger-hours aloft. With an effective dose rate of 2.8 μSv h^{-1} at 8 km, calculated using equations (1) and (3), the collective effective dose from global air travel is about 10,000 man Sv for the year. Worldwide, the annual value of the per caput effective dose due to air travel is, therefore, about 2 μSv; in North America it is around 10 μSv. These values are small in comparison to the estimated annual per caput effective dose at ground level of 380 μSv.

31. A limited number of supersonic airplanes operate commercially and cruise at about 15 km. Doses on board are routinely determined with monitoring equipment. Effective dose-equivalent rates are generally around 10 μSv h^{-1}, with a maximum around 40 μSv h^{-1} [U1]. In two years from July 1987, the overall average on six French airplanes was 12 μSv h^{-1}, with monthly values up to 18 μSv h^{-1} [S11]; in 1990, the average was 11 μSv h^{-1} and the annual dose to aircrew was about 3 mSv [M16]. During 1990, the average dose rate for about 2,000 flights by British airplanes was 9 μSv h^{-1}, with a maximum value of 44 μSv h^{-1} [D4]. The equivalent dose rates so far reported in this paragraph do not take into account the changes in the radiation weighting factors for neutrons that were recommended by ICRP in 1991 [I6]. The effective dose rates, estimated with the new radiation weighting factors for the neutron component, are higher than the numerical values reported above by about 30%. The monitoring equipment serves to warn of solar flares so that the airplanes can be brought to lower altitudes. This is a very small sector of the commercial air transport industry.

B. COSMOGENIC RADIONUCLIDES

32. Cosmic rays produce a range of radionuclides in the atmosphere, biosphere and lithosphere by a variety of nuclear reactions. The four most important radionuclides in terms of dose are ^{3}H, ^{7}Be, ^{14}C and ^{22}Na, and the most important mechanism of human exposure is ingestion.

33. The most significant of the four radionuclides considered is ^{14}C. The assessment of its contribution to the dose from natural sources is useful for the derivation of doses from man-made environmental releases of ^{14}C. The annual natural production of ^{14}C is 1 PBq and the specific activity of ^{14}C is 230 Bq per kg of carbon, leading to an annual effective dose of 12 μSv [U4]. The spatial variability of the dose from ^{14}C is not radiologically significant.

34. Annual effective doses to adults from the ingestion of ^{3}H, ^{7}Be and ^{22}Na in food and water have been derived from estimated average annual intakes [N2, U3, U4], applying standard coefficients for dose per unit intake [I4, N5] and assuming an equilibrium situation. The annual effective doses obtained for those three radionuclides are much smaller than that for ^{14}C. The annual intakes and effective doses for the four cosmogenic radionuclides are summarized in Table 3.

C. SUMMARY

35. Cosmic rays, which originate in space, and solar particles enter the earth's atmosphere and begin a cascade of secondary interactions and decays. The resultant ionization is a function of both altitude and latitude. The ionizing component of cosmic rays produces, on average, an absorbed dose rate in air of 32 nGy h^{-1} at sea level in the mid-latitudes, corresponding to an effective dose rate of 32 nSv h^{-1}. The neutron component of cosmic rays results in an effective dose rate of 3.6 nSv h^{-1}. The intensities of both components increase with altitude, more so for the neutron component.

36. Taking into account shielding by buildings for the ionizing component and the distribution of world population with altitude, the population-weighted average annual effective dose from cosmic rays is 380 μSv. The effective dose rate received during a commercial flight is about 3 μSv h^{-1}; the per caput annual effective dose for the world population due to air travel is 2 μSv.

37. Exposures to cosmogenic radionuclides, produced by cosmic ray interactions in the atmosphere, result primarily from ingestion and are relatively uniform throughout the world. The radionuclides include ^{3}H, ^{7}Be, ^{14}C and ^{22}Na. The annual effective dose from ^{14}C is 12 μSv. Exposure from the other radionuclides is negligible.

II. TERRESTRIAL RADIATION

38. Only nuclides with half-lives comparable with the age of the earth (or decay products, whose concentrations are governed by them) exist in terrestrial materials. In terms of dose, the principal primordial radionuclides are ^{40}K (half-life: 1.28 10^{9} a), ^{232}Th (half-life: 1.41 10^{10} a) and ^{238}U (half-life: 4.47 10^{9} a). Of secondary importance are ^{87}Rb (half-life: 4.7 10^{10} a) and ^{235}U (half-life: 7.04 10^{8} a). The thorium and uranium radionuclides head series of several radionuclides, many of which contribute to human exposure. The decay series headed by ^{238}U and ^{232}Th were illustrated in the UNSCEAR 1988 Report [U1]; the radionuclides in the series headed by ^{235}U are less important from a dosimetric point of view. There may be some local departure from secular radioactive equilibrium in the series because of physicochemical processes in the earth, such as leaching and emanation. The mass ratio of natural ^{235}U to ^{238}U is about 0.0073 and the activity ratio 0.046. A slight degree of spontaneous fission occurs in the uranium series. Both ^{40}K and ^{87}Rb undergo beta decay to stable species.

39. Natural radionuclides are also present to varying degrees in the air, in water, in organic materials and in living organisms. Human beings are therefore exposed to external and internal irradiation by gamma rays, beta particles and alpha particles with a range of energies. The main circumstances of external and internal exposures are considered in this Chapter. Separate consideration is given in Chapter III to the inhalation of the radon isotopes in the uranium and thorium series.

A. EXTERNAL EXPOSURE

1. Outdoors

40. Exposure to gamma rays from natural radionuclides occurs outdoors and indoors. Surveys by direct measurements of dose rates have been conducted during the last few decades in many countries. They are summarized in Table 4 and illustrated in Figure II. For the doses outdoors three

fifths of the population of the world is represented. National averages range from 24 to 160 nGy h^{-1}. The population-weighted average is 57 nGy h^{-1}. This is little different from the value of 55 nGy h^{-1} estimated in the UNSCEAR 1988 Report [U1].

41. In the open, much human exposure occurs over paved surfaces, but some also occurs over soil; it is determined by the activity per unit mass of the principal radionuclides in the superficial layer. Large surveys of natural radionuclides in surface soils were carried out in the United States [M1] and in China [N22]; the results are presented in Table 5. Samples were taken from fallow land. Variability is quite marked. Similar mean values for uranium and radium are reported for the United States and China, but the mean values for thorium and potassium are somewhat higher in China than in the United States, and the distributions are wider.

42. In the UNSCEAR 1988 Report, the average concentrations of ^{238}U and ^{232}Th in soil were taken to be 25 Bq kg^{-1} for each radionuclide. Although it is difficult to estimate average concentrations for the wide distributions presented in Table 5, it seems that 40 Bq kg^{-1} would be a better estimate of the average concentration of ^{238}U and ^{232}Th in soil. Data on the concentrations of naturally occurring radionuclides in various types of soils in the Nordic countries, presented in Table 6, are in agreement with the revised estimate.

43. The dose rates per unit activity concentrations of radionuclides have been calculated; for example, Monte Carlo calculations give the kerma in air for terrestrial gamma rays [P2, S12]. Since the mass energy transfer and absorption coefficients for air are not notably different in the energy range of interest here, these coefficients may be deemed compatible with those for absorbed dose rate in air used in the UNSCEAR 1988 Report [U1, B3]. When these dose factors, which are included in Table 5, are applied to the radionuclide concentrations in soil, the average dose rates in air are 72 and 55 nGy h^{-1} in China and the United States, respectively. According to Table 4, the population-weighted average absorbed dose in air for China was 62 nGy h^{-1} and that for all countries reporting survey results 57 nGy h^{-1}. Since human habitations are mostly in areas of sedimentary geology and since radionuclide concentrations in bedrock and overburden are similar in such circumstances [W2], the values from Table 5 in the narrower range, 10-200 nGy h^{-1}, may be considered to be broadly typical for the world population. Areas of high activity are discussed later.

44. The water content of the soil and snow cover can affect absorbed dose rates in air. On the whole, increasing water content and snow cover reduce dose, but these are second-order phenomena [D3, F3, G2] when averaged over a year in temperate zones with moderate precipitation. In extreme climates with heavy snow cover, however, the reduction may be as much as 20% [S5, S35]. The addition of phosphate fertilizer, discussed in Section IV.C, may cause a second-order increase in dose rate [P3].

45. Areas of markedly high absorbed dose rates in air around the world are associated with thorium-bearing and uranium-bearing materials. Mineral sands containing monazite are prime examples of the former. Absorbed dose rates in air from gamma rays near separated monazite may reach 10^5 nGy h^{-1} depending on geometry [M6]. It is not surprising, therefore, that dose rates over sands can be remarkable. Two such areas are well known: on the Arabian Sea coast of Kerala in India, where dose rates in air range from 200 to 4,000 nGy h^{-1} [S6, S7] and on the Atlantic coast of Espírito Santo in Brazil, where dose rates in air range from 100 to 4,000 nGy h^{-1} approximately [P4]. Radiation exposures due to mining and milling of mineral sands are discussed in Section IV.D.

46. Other areas of high background radiation have also been identified. On the Nile Delta, dose rates in air are estimated to range from 20 to 400 nGy h^{-1} [E2] and on the Ganges Delta from 260 to 440 nGy h^{-1} [M7]. Dose rates in air of up to 12,000 nGy h^{-1} have been reported over thorium-bearing carbonatite in an area near Mombasa on the coast of Kenya [P6]. An area of volcanic intrusives in Minas Gerais, Brazil, with mixed thorium and uranium mineralization, has dose rates in air roughly from 100 to 3,500 nGy h^{-1} [P17]. Ramsar, on the Caspian Sea in Iran, has dose rates up to 30,000 nGy h^{-1} because of thorium and uranium deposition by hot springs in travertine [S33]. Many granite areas have elevated natural radiation levels [M2, W10]. Localized dose rates in air around 100,000 nGy h^{-1} have been found over uraniferous rocks in Sweden [S8]. Dose rates associated with uraniferous phosphate deposits are appreciably lower; on the phosphate lands of Florida, they range from 30 to 100 nGy h^{-1} [N2].

2. Indoors

47. During the last decade, several surveys have been made of the dose rate in air from terrestrial gamma rays inside dwellings. The results are included in Table 4. Over a third of the world population is represented. The surveys are not quite as complete as outdoor investigations. National averages range from 20 to 190 nGy h^{-1} with a population-weighted average of all the data being about 80 nGy h^{-1}. This value is somewhat higher than 70 nGy h^{-1}, selected in the

UNSCEAR 1988 Report [U1] as representative for indoor exposure worldwide.

48. In comparing the indoor and outdoor averages, it is seen that the overall effect of surrounding building materials is to increase the dose rate 40%-50%. As indicated in Table 4 and illustrated in Figure III, the ratio of indoor to outdoor dose rates varies from 0.8 to 2.0. In only two countries, Iceland and the United States, are average absorbed dose rates indoors judged to be less than outdoors. This ratio is sensitive to the structural properties of dwellings (materials, thicknesses and dispositions) and is of limited utility for estimating exposures in particular cases from outdoor data. However, the relatively narrow range of the indoor-outdoor ratio reflects the fact that building materials are usually of local origin and that their radionuclide concentrations are similar to those in local soil. The building materials act as sources of radiation and also as shields against outdoor radiation. In wooden and lightweight houses, the source effect is negligible and the walls are an inefficient shield with respect to the outdoor sources of radiation, so that the absorbed dose rate in air could be expected to be somewhat lower indoors than outdoors. In contrast, in massive houses made of brick, concrete or stone, the gamma rays emitted outdoors are efficiently absorbed by the walls, and the indoor absorbed dose rate depends mainly on the activity concentrations of natural radionuclides in the building materials. Under these circumstances, the indoor absorbed dose rate is generally higher as the result of the change in source geometry, with the indoor-outdoor ratio of absorbed dose rates in air between 1 and 2.

49. There is considerable uncertainty in estimates of indoor dose rates. It is clear that the dose rates in masonry dwellings are appreciably higher than in wooden ones, as explained in the previous paragraph. For improved estimates of doses, it would be necessary to have data for representative housing stock around the world. Data for houses in warm climates are underrepresented in Table 4; these may be constructed very differently from houses in cold climates. It is expected that the percentage of houses that are largely made of wood and other lightweight materials is greater in warm climates than in cold climates, so that for the same average absorbed dose rate in air outdoors, the average absorbed dose rate in air indoors would be lower in warm climates than in cold climates. This needs to be confirmed by measurements. Such an important source of human exposure should be quantified more extensively.

50. The dose rates in masonry dwelling are determined by the characteristics of the masonry materials: 30 g cm^{-2} of masonry, for example, provides 90% of the gamma rays from an infinitely thick source [N2]. If construction materials with elevated concentrations of natural radionuclides are used, dose rates in air indoors will be elevated accordingly. Some measurements have been made of dose rates in relation to building materials. Measurements in Sweden gave values of about 230 nGy h^{-1}, on average, in houses with outside walls made of lightweight concrete, some of which contained uraniferous alum shale [M9, M27]. Measurements in former Czechoslovakia gave values approaching 1,000 nGy h^{-1} in houses with outside walls containing uraniferous coal slag [T3]. Measurements in a granite region of the United Kingdom, where some of the houses are made of local stone, gave 100 nGy h^{-1} [W3]. Estimates for houses made with mud blocks in Jamaica reach 200 nGy h^{-1} [P18]. It is useful, therefore, to calculate the effect of using building materials with different activity characteristics.

51. In round terms, the activities per unit mass of ^{40}K, ^{226}Ra and ^{232}Th in building materials A_K, A_{Ra}, and A_{Th} are typically 500, 50 and 50 Bq kg^{-1}, respectively [N10]. If the dose coefficients given in Table 5 are applied, it is possible to construct an activity utilization index that facilitates the calculation of dose rates in air from different combinations of the three radionuclides in building materials. This may then be weighted for the mass proportion of the building materials in a house. The activity utilization index is given by the expression

$$\left(\frac{C_K}{A_K} f_K + \frac{C_{Ra}}{A_{Ra}} f_{Ra} + \frac{C_{Th}}{A_{Th}} f_{Th}\right) w_m \qquad (4)$$

where C_K, C_{Ra} and C_{Th} are actual values of the activities per unit mass of ^{40}K, ^{226}Ra and ^{232}Th in the building materials considered (Bq kg^{-1}); f_K, f_{Ra} and f_{Th} are the fractional contributions to the dose rate in air from the standard or typical concentrations of these radionuclides; and w_m is the fractional usage of the building materials in the dwelling with the activity characteristic. For full utilization of typical masonry, the activity utilization index is unity by definition and is deemed to imply a dose rate of 80 nGy h^{-1}. In Table 7, illustrative examples are given of the use of the activity utilization index.

52. To estimate the effect of using atypical materials, it is necessary to determine the fractional utilization by mass, identify the associated dose rate and then subtract the corresponding dose rate for typical masonry. Thus, 0.5 utilization of granite would increase the dose rate by 70 - 40 = 30 nGy h^{-1} and 0.5 utilization of alum shale would increase it by 390 - 40 = 350 nGy h^{-1}. One quarter utilization of

phosphogypsum would cause an increase of 50 nGy h^{-1}, but a similar fraction of natural gypsum would lead to a decrease of 15 nGy h^{-1}. Because of the simple irradiation geometry and rounded parameter values, this approach is only very approximate, but there is some experimental confirmation [E3], and it does describe the circumstances mentioned earlier.

53. In Kerala, some of the more radioactive stretches of sand have concentrations of ^{40}K, ^{226}Ra and ^{232}Th of 100, 1,000 and 7,000 Bq kg^{-1}, respectively [L6], which would lead, according to the foregoing formulation, to 5,000 nGy h^{-1} in dwellings, since structures there provide little shielding against gamma rays from the ground. Measured dose rates in air in an earlier survey approached 4,000 nGy h^{-1}, with an arithmetic mean around 700 nGy h^{-1} for the population on the segment of the coast with the most radioactive sand [S6]. Large-scale surface mining and subsequent refilling with monazite-free tailings have, however, reduced the external radiation fields substantially, e.g. at some locations from 4,000 nGy h^{-1} to 300 nGy h^{-1}, and improvements in socio-economic conditions have resulted in structural modifications of the hutments, which have reduced indoor external radiation exposures by a factor of 3 [P6].

54. Some of the short-lived decay products of ^{222}Rn, always present in air, emit gamma rays. A semi-empirical analysis for a single-family house yielded an absorbed dose rate in air of 0.01 nGy h^{-1} per unit activity concentration of radon progeny at equilibrium expressed as Bq m^{-3} [M10]. For 20 Bq m^{-3}, a representative activity concentration indoors, the dose rate would be about 0.2 nGy h^{-1}, which is relatively trivial in relation to direct gamma rays from the building materials and the dose to human lungs from alpha particles emitted by the other radon progeny. Another semi-empirical estimate for gamma rays from radon progeny outdoors yielded an increment of 0.5% per Bq m^{-3} over the fluence rate of photons directly from the earth [N11]. For an equilibrium equivalent concentration outdoors of 8 Bq m^{-3}, this implies a dose rate increment of 2 nGy h^{-1}, that is, a few per cent of the prevailing dose rate from the earth. Monte Carlo calculations [F12] substantiate these estimates.

3. Dose

55. In the UNSCEAR 1988 Report [U1], a coefficient of 0.7 Sv Gy^{-1} was used to convert absorbed dose in air to effective dose equivalent. This refers to adults and is based on an analysis in the UNSCEAR 1982 Report [U3] of experimental and calculational data on environmental exposure to gamma rays. A more recent assessment [P19, S12] provides coefficients for exposure to terrestrial gamma rays not only for adults but also for children and infants. Reference data are given in Table 8. The overall value is not altered appreciably by weighting for the typical radionuclide composition of soil. These results were derived from Monte Carlo calculations for mathematical phantoms, those for adults being based on ICRP Reference Man [I5] and those for the younger persons on computed tomographic data for patients. In round terms, therefore, the conversion coefficient of 0.7 Sv Gy^{-1} still seems to be suitable for adults [U1]. Because of the circumstance of irradiation, it seems unlikely that the conversion coefficient to effective dose would differ appreciably from this value.

56. The assumption has been made in previous UNSCEAR Reports [U1, U3, U4] that the indoor occupancy factor is 0.8, implying that 20% of time is spent outdoors, on average, around the world. There is no way at present of validating this assumption, but the indications are that 0.8 is low for industrialized countries in temperate climates, where an appreciable fraction of time is spent indoors in structures other than the home [N2, W3], and high for agricultural countries in warm climates, where a substantial fraction of time is spent out of doors even at night [E5]. As more information becomes available, it may be possible to refine the estimate of the occupancy factor, but at present there is no basis for changing the conventional value.

57. With values for the conversion coefficient to effective dose (0.7 Sv Gy^{-1}) and the occupancy factor (0.8), it is possible to combine outdoor (57 nGy h^{-1}) and indoor (80 nGy h^{-1}) exposures to terrestrial gamma rays to estimate the average effective dose. The arithmetic annual mean worldwide, weighted for population, is 0.46 mSv, somewhat higher than the value for cosmic rays (0.38 mSv), the other component of external exposure to natural radiation sources. For children and infants, the values are about 10% and 30% higher.

58. It is of interest to present some national estimates of average annual effective dose from terrestrial gamma rays. This is done in Table 9. The underlying assumption in each case that the effective dose equivalent and the effective dose are numerically the same for this circumstance. The values range from 0.23 to 0.65 mSv, with a median value of 0.40 mSv. The population-weighted value for these 13 countries is 0.45 mSv, in agreement with the result quoted in the previous paragraph.

59. To complete the consideration of the external component of natural background exposure, the doses

from external irradiation by environmental beta particles should be mentioned, although these mainly affect the superficial tissues of the body. Calculations for soil show that the absorbed dose rate in air from beta particles is similar at the surface of the ground to that for gamma rays, but that it drops to 20% of the latter at 1 m above the surface [O4]. Furthermore, the dose throughout the organs of the body generally is about two orders of magnitude less than the dose to the skin. Similar circumstances exist indoors. The absorbed dose rate from airborne beta emitters is comparable to that from surface emission indoors and about an order of magnitude less outdoors. If these relationships are applied to the average values for the absorbed dose rates from gamma rays outdoors and indoors, the annual absorbed dose to the skin from beta particles is estimated to be about 0.2 mGy overall. The contribution to dose from beta particles from the surfaces of particular materials, such as the mineral sands in Kerala, would be much more [S7].

B. INTERNAL EXPOSURE

60. After cosmic rays and terrestrial gamma rays, the third element of basic background exposure is that from long-lived natural radionuclides in the human body, which arises from inhalation and ingestion. Potassium-40 and the uranium and thorium series radionuclides are treated separately. Radon is considered in Chapter III.

61. Data on ^{40}K in the human body are well established, mainly from direct measurements of persons of various ages [I5, U5] but also from the analysis of post-mortem specimens [F13]. At the age of 30 years, approximately the median for industrialized countries [U11], the body content of potassium is about 0.18%, at 10 years about 0.2%, and is assumed to be the same at 1 year, these being the averages for the sexes. Potassium is under homeostatic control in the body, although there are disease states that affect the level. The isotopic abundance of ^{40}K is $1.18\ 10^{-4}$. With an average specific activity of 55 Bq kg^{-1} of body weight and a rounded conversion coefficient of 3 μSv a^{-1} per Bq kg^{-1} [N2], the annual effective dose equivalent from ^{40}K in the body is 165 μSv for adults, most of the dose being delivered by beta particles. The value for children is 185 μSv.

62. Doses from radionuclides in the uranium and thorium series, on the other hand, reflect intake to the body with diet and air. In previous UNSCEAR Reports [U1, U3, U4, U5], doses were estimated from measured activities in tissues and appropriate dosimetric coefficients, but intake data were also provided. In this Annex, intake data are translated to committed effective doses for adults and also for children and infants, so as to indicate the effect of intake with age. Although the determination of dose from concentrations in tissue is more direct, the data on intake provide a good secondary indication.

63. A reference food consumption profile is presented in Table 10. This is based on the normalized average consumption rate adopted by WHO [W4], derived from the food balance sheets compiled by the Food and Agriculture Organization (FAO) [F4]. These estimates refer to raw, unprepared products with no account taken of losses in distribution and utilization; consequently, average values are usually overestimates. Data on food consumption by age are usually obtained from nutritional studies, but because the information is rather limited, relative rather than absolute values are best inferred [V2]. In Table 10, therefore, the average values [W4] are adopted for adults, and the consumption rates for children and infants are taken to be two thirds and one third of the adult values, except for milk products, which are higher than unity [V2]. Intakes of water, both directly and in beverages, are based on reference ICRP water balance data [I5]. The tabulated values are compatible with other assessments [C4, N13, U1]. There are, of course, departures from the reference consumption: the Chinese diet, for example, is low in milk, the African diet in leafy vegetables [W4] and the Indian diet in meat [R11]. Cereal consumption, on the other hand, is much the same in all types of diet. The nominal nature of the data in Table 10 and the resulting uncertainties in the dose estimates must be stressed. Reference ICRP breathing rates [I5] are also given in Table 10.

64. The next step is to establish reference activity concentrations in dietary materials and air. The values for food and water in Table 11 rely heavily on data for northern temperate latitudes [F5, L5, N2, P5, P20, S13, S14, S44] and are compatible with data in the UNSCEAR 1988 Report [U1]; fish, for which data are scarce and disparate, includes a 10% admixture of invertebrates [C5, J7]. All food values are for wet weight. Reference concentrations in air in Table 11 are from the same sources [F5, L5, N2, U1] and are deemed to apply outdoors and indoors.

65. Information on effective dose per unit intake of activity of naturally occurring radionuclides by adults is given in Table 12 [I4]; it is based on the biokinetic models of ICRP. It is assumed in this Annex that the doses per unit activity intake for natural radionuclides are not age-dependent.

66. Average age-weighted annual intakes by ingestion and associated effective doses have been estimated using the fractional distribution of adults, children and infants of 0.65, 0.3 and 0.05, respectively; the results are presented in Table 13. The intake values are generally similar to those in the UNSCEAR 1988 Report [U1], although the ^{210}Po value is

somewhat higher, mainly because fish and, in particular, invertebrates were included. The dominant radionuclides are ^{210}Pb and ^{210}Po. There is a scarcity of environmental data for ^{231}Pa and ^{227}Ac [K10, V7], but if they were present to the same degree as ^{235}U, the overall effective dose would be increased by approximately 1%. Along the same line, the intake of ^{228}Th has been assumed to be equal to that of ^{232}Th. In fact, the intake of ^{228}Th should be greater, because of some ingrowth of that radionuclide in foodstuffs following the decay of ^{228}Ra [L11]; this ingrowth, which is difficult to quantify, would result in an increase in the overall effective dose of less than 2%.

67. Table 13 includes analogous information for inhalation. The values are similar to those in the UNSCEAR 1988 Report [U1]. The dominant radionuclide is ^{210}Pb. It may be noted that smoking 10 cigarettes a day would double the intake of ^{210}Po [N2]. The decay products of ^{235}U would, once more, add about 1%.

68. The doses from reference annual intakes of the long-lived series radionuclides can be compared to the annual doses re-estimated from the UNSCEAR 1988 Report [U1] with the new ICRP tissue weighting factors [I6]. For uranium and thorium series radionuclides, the effective doses are 62 μSv committed from annual intake and 130 μSv annually from average body content. For ^{40}K the same doses are 170 and 180 μSv, respectively. The total effective doses are 230 μSv by intake and 310 μSv by body content. The results are fairly consistent and support the validity of the intake estimation method. The advantages of this method over that based on post-mortem analyses are that there are more data on activities in foodstuffs than in human tissues and that it facilitates the estimation of doses from high intakes of activity in unusual circumstances. It is recognized, however, that there are large uncertainties in the values of the dose coefficients, mainly owing to uncertainties in the values of the gut absorption fractions (also called f_1) for many radionuclides. These uncertainties may arise for a variety of reasons, including the chemical nature of the radionuclide ingested, biological variability in humans and extrapolation from animal data when human data are sparse. It would be desirable to carry out more post-mortem analyses of tissues to determine natural radionuclide concentrations, as such analyses would allow a more direct assessment of the absorbed doses.

69. The variability of activity concentrations in foods is clearly shown in Table 14, where selected information on elevated levels is presented. The reference values can be exceeded by orders of magnitude. In the volcanic area of Minas Gerais, Brazil [A4, A8, L10, V3] and in the mineral sands area of Kerala, India [L6], there is evidence of excess activity in milk, meat and grain, leafy vegetables, roots and fruits. In the granitic area of Guandong, China, excess activity has been reported in foodstuffs such as rice and radishes [Z1]. Mention might also be made of the elevated levels of ^{210}Po in yerba maté, a plant used to make a beverage in South America [C15]. For radiological significance, however, the most pronounced increase over reference levels occurs in the Arctic and sub-Arctic regions, where ^{210}Pb and ^{210}Po accumulate in flesh of reindeer and caribou [H7, P7], an important part of the diet of the inhabitants of those regions. Reindeer and caribou feed on lichens, which accumulate these radionuclides from the atmosphere. If the annual consumption of reindeer and caribou meat is taken into account [K3], it is possible to evaluate the effective dose from this intake. Assuming the reference intakes for other foods and water apply, the overall dose from ingestion is estimated to be about 300 μSv for adults. This is one example of a community exposed under unusual circumstances.

70. Selected information on elevated levels of activity concentrations in potable waters is shown in Table 15 with values for some bottled mineral waters and ground waters. These elevated levels are to be compared with the reference levels presented in Table 11. As with foods, reference values are exceeded by orders of magnitude. Bottled waters in Brazil include some from areas of high natural radiation levels [P8]. The results for France [M19, P5, P9, R12, R13, R14, S11] represent all the principal sources of mineral waters in that country. Commercially available waters were widely sampled in Germany [B12, G4, G5]. The selection of Portuguese waters was broadly representative [B6]. An extensive survey in Sweden of public and private water supplies [K4] yielded high levels of ^{226}Ra in some wells with an average of 45 mBq kg^{-1} in water from deep-bored wells. In Finland, remarkably high concentrations have been discovered in wells drilled in bedrock throughout the south of the country near Helsinki [S15]. If allowance is made for the extra dose from these waters with otherwise reference intakes, the overall value of the committed effective dose becomes 550 μSv for annual intakes by adults. This is another example of a community with unusual circumstances of exposure.

C. SUMMARY

71. Natural radionuclides of significance in soil, air, water and living organisms include ^{40}K and the isotopes of the ^{238}U and ^{232}Th decay chains. Exposures occur by external irradiation and from internal irradiation following ingestion or inhalation of the radionuclides.

72. The dose rate in air outdoors from terrestrial gamma rays in normal circumstances is around 57 nGy h^{-1}. National averages range from 24 to 160 nGy h^{-1}. Soil and survey data yield similar values. Communities living on mineral sands may well be exposed at two orders of magnitude more. The gamma-ray dose rate indoors is estimated to be 80 nGy h^{-1}, the population-weighted mean of measured values worldwide, and the range of reported national averages is 20-190 nGy h^{-1}. These results are in accordance with values inferred from outdoor measurements and the concentrations of radionuclides in building materials. Applying a coefficient of 0.7 Sv Gy^{-1} to convert absorbed dose rate in air to effective dose and using an indoor occupancy factor of 0.8, the world-wide average annual effective dose from external exposure to terrestrial radionuclides is 0.46 mSv.

73. Effective doses resulting from intake of natural radionuclides in air, food and water may be determined from measured concentrations in the body or estimated from concentrations in intake materials. The worldwide average committed dose from annual intakes is estimated to be 0.23 mSv, of which 0.17 mSv is from ^{40}K and 0.06 mSv from radionuclides of the ^{238}U and ^{232}Th series. Variations in exposures occur from variations in the latter component. Communities receiving higher effective doses include consumers of reindeer meat (average annual effective dose: 0.3 mSv) and consumers of deep well water in some locations (average annual effective dose: 0.5 mSv). Little information exists on the variability of dose from the inhalation of long-lived activity in air, but inhalation is dominated by radon isotopes and their short-lived decay products, which are the subject of the next Chapter.

III. RADON

74. Exposure to radon is the most significant element of human irradiation by natural sources. It is distinguished from the other three elements of basic background because exposure varies markedly in ordinary circumstances and because high exposures may be avoided with comparative ease. The most important mechanism of exposure is the inhalation of the short-lived decay products of the principal isotope, ^{222}Rn, with indoor air. Concentrations of ^{222}Rn and its progeny are usually higher in indoor air than in outdoor air; exceptions are in tropical areas, where ^{222}Rn concentrations in well-ventilated dwellings are essentially the same as in outdoor air.

75. There are three natural isotopes of the radioactive element radon: ^{219}Rn (actinon) in the ^{235}U series; ^{220}Rn (thoron) in the ^{232}Th series; ^{222}Rn (radon) in the ^{238}U series. Because of the low activity concentrations of ^{235}U and the short half-life of ^{219}Rn, this isotope is not significant for human exposure. Because of its short half-life, ^{220}Rn is of concern only where the concentration of ^{232}Th is high. Owing to its relatively long half-life, ^{222}Rn is the most significant isotope, and there is much information on it. Table 16 gives the alpha decay properties of ^{220}Rn and ^{222}Rn and their short-lived decay products [B7, M11].

76. Radon is a noble gas with slight ability to form compounds under laboratory conditions [S16]. The density of radon is 9.73 g l^{-1} at 0° C [W5]. There is very little radon in air, typically about one atom per 10^{18} atoms of air indoors, and so it does not stratify. Its solubility in water at 0° C is 510 cm^3 l^{-1} decreasing to 220 cm^3 l^{-1} at 25° C and 130 cm^3 l^{-1} at 50° C.

A. SOURCES AND MOVEMENT

1. Production in terrestrial materials

77. The production of ^{220}Rn and ^{222}Rn in terrestrial materials depends on the activity concentrations of ^{228}Ra and ^{226}Ra present. Indicative values for these radium isotopes in soils may be inferred from Table 5. Some values for rocks, taken from extensive analyses [C14, W6], are given in Tables 17 and 18. On average, granites are high in radium, basalts are low and sedimentary and metamorphosed rocks have intermediate values. In the main, the results are fairly consistent with the soil values, although exceptional values of ^{226}Ra do occur in some detrital sedimentary rocks [A5].

78. Earth materials may be envisaged as a porous matrix through which fluids can move. To be free to do so, radon must first emanate from the mineral substance into the pore space. This is brought about mainly by the recoil of radon atoms on formation, with a typical range of 20-70 nm in minerals, and by molecular diffusion [T4]. Emanation is thought to be amplified by the superficial disposition of radon precursors and the damage caused by radioactive decay. The fraction of radon formed that enters the pores has variously been called the emanating power, the ratio, the coefficient and the fraction. Values of the emanation fraction, as it is called here, for various earth and building materials are given in Table 19. The results relate to ^{222}Rn and are supported by other studies of soils [B13, M20, M21]. Relatively little

information exists for ^{220}Rn, but similar values would be expected because of the physical processes involved.

79. Moisture and temperature affect radon emanation. The presence of water increases the probability that the recoils will terminate in the pores rather than the matrix and that more radon will therefore be available for movement [T4], but this trend is later reversed as the water content grows. Increasing temperature also increases emanation, probably because of reduced adsorption, but the mechanism and magnitude of this effect are not as well understood or quantified [S18]. Of the two, the moisture effect is the more significant.

2. Diffusion

80. The movement of radon in porous material is brought about by concentration and pressure gradients; the mechanisms of movement are molecular diffusion and forced advection [N14]. Both are modified by radioactive decay. Consideration here is limited to the movement of radon from the ground into the open atmosphere and from the ground and building elements into confined spaces such as dwellings. Attention is first given to diffusion.

81. If earth is regarded as a porous mass of homogeneous material semi-infinite in extent, the flux density of radon at the surface J_D (Bq m^{-2} s^{-1}) is given [U1] by the expression

$$J_D = C_{Ra} \lambda_{Rn} f \rho [D_e / (\lambda_{Rn} \varepsilon)]^{0.5} \qquad (5)$$

where C_{Ra} is the activity concentration of ^{226}Ra in earth material (Bq kg^{-1}); λ_{Rn} is the decay constant of ^{222}Rn (2.1 10^{-6} s^{-1}); f is the emanation fraction for earth material; ρ is the density of earth material (kg m^{-3}); D_e is the effective diffusion coefficient for earth material (m^2 s^{-1}); and ε is the porosity of the earth material. The first four parameters in the equation comprise the volumetric production rate of radon (Bq m^{-3} s^{-1}); the expression in brackets is the diffusion length.

82. If a building element, such as a wall or floor, is similarly regarded as a semi-infinite slab of porous material, the flux density of radon from one side is given [U1] by the expression

$$J_D = C_{Ra} \lambda_{Rn} f \rho [D_e / (\lambda_{Rn} \varepsilon)]^{0.5} \tanh d [D_e / (\lambda_{Rn} \varepsilon)]^{-0.5} \qquad (6)$$

where d is the half-thickness (in metres) of the element and the other symbols refer to the same parameters as in equation (5), but where the values are for the building material rather than the earth material. The two equations are the same apart from the hyperbolic term, which takes into account the finite thickness of the slab and has a value less than unity.

83. Since diffusion dominates over advection as the mechanism by which radon enters the atmosphere from the surface of the earth [N14], it is possible to calculate the flux density by using appropriate values for the parameters in equation (5). Values of C_{Ra} are in Table 5 and values of f, D_e and ε in Table 19. Representative values are C_{Ra} = 40 Bq kg^{-1}; f = 0.2; D_e = 5 10^{-7} m^2 s^{-1}; ε = 0.25. The value of ρ is about 1,600 kg m^{-3}, and λ_{Rn} = 2.1 10^{-6} s^{-1}. These yield an estimate for J_D of 0.026 Bq m^{-2} s^{-1}, somewhat higher than the weighted value of 0.016 Bq m^{-2} s^{-1} from measurements over various soils [W7] but quite close to the average value of 0.022 Bq m^{-2} s^{-1} estimated for Australia [S36] and compatible with the indications for sedimentary areas of France [R15]. It must be noted, however, that the calculated value of J_D is critically dependent on the value adopted for C_{Ra} and that the measured value is critically dependent on the weighting procedure for soil type. The volumetric production rate, given by the first part of the equation, is about 0.027 Bq m^{-3} s^{-1}.

84. For building elements, the flux density due to diffusion may be calculated by substituting the appropriate values in equation (6). Such values of C_{Ra}, f, D_e and ε are in Tables 7 and 19: C_{Ra} = 50 Bq kg^{-1}; f = 0.1; D_e = 1 10^{-8} m^2 s^{-1}; ε = 0.15. As before, λ_{Rn} = 2.1 10^{-6} s^{-1}, and the value of ρ is taken to be 1,600 kg m^{-3}; for elements 0.2 m thick, d is 0.1 m. These yield an estimate for J_D of 0.0015 Bq m^{-2} s^{-1} and a volumetric production rate of 0.017 Bq m^{-3} s^{-1}. Whereas the production rate is comparable to the volumetric value for earth material, the flux density from a building material element is about an order of magnitude less. Volumetric production rates for radon inferred from measurements on laboratory specimens of ordinary concrete are in accordance with the calculated value, but the rates for natural gypsum and ordinary clay bricks are lower than estimated [C6, J2, T5, U1]. Most measurements of radon flux density have been made on laboratory specimens of building materials; since these have a much higher surface-to-volume ratio than building elements, the results underestimate the flux density in practical circumstances [C6]. Some measurements on sections of building elements do, however, give results that are fairly compatible with the calculations for ordinary concrete and ordinary clay bricks but appreciably lower for natural gypsum [B9, P10, S20].

85. As in the UNSCEAR 1988 Report [U1], a model building is defined so as to illustrate the relative importance of the various sources of radon indoors. A

simple masonry structure is envisaged with a volume, V, of 250 m^3 and a surface area, S_B, of 450 m^2. The characteristics broadly reflect construction in temperate climates. An air exchange rate of 1 h^{-1} is postulated. The rate U of radon entry from the building elements (Bq m^{-3} h^{-1}) is given by the expression

$$U = (3.6\ 10^3\ S_B J_D)/V \qquad (7)$$

where J_D is defined in equation (6). The resulting value of U is almost 10 Bq m^{-3} h^{-1}. Without a masonry floor, the rate of entry by diffusion from bare earth would be about 37 Bq m^{-3} h^{-1}, this being calculated by substituting the surface area of the floor, S_E = 100 m^2, for S_B and 0.026 Bq m^{-2} s^{-1} for J_D in equation (7). An intact concrete floor 0.2 m thick would, however, reduce the rate of entry by a factor of about 14 [C7, U1] to 2.6 Bq m^{-3} h^{-1}, which is comparable to the contribution from such a floor element.

86. It should be recognized that floors are unlikely to be intact and that holes and cracks greatly facilitate the entry of radon. The effect of cracks has been modelled in a mathematical sense for a stylized pattern of penetrations through a floor element [D6, L8]. With an array of 1 cm wide cracks every 1 m through a 0.2 m thick floor and a diffusion coefficient of 5 10^{-7} m^2 s^{-1} for the underlying earth, the rate of entry by diffusion is about 20% of that from bare earth [D6], implying 7.5 Bq m^{-3} h^{-1}, which in turn implies a flux density, averaged over the whole floor, of 0.0052 Bq m^{-2} s^{-1}. In the reference building, therefore, 1% discontinuity in the floor permits 20% diffusion from the earth.

3. Advection

87. Attention is now turned to the forced advection (also frequently called convection) of radon from the earth into a building. This is caused by the slightly negative pressure differences (underpressure) that usually exist between the indoor and outdoor atmospheres. Two mechanisms are mainly responsible, wind blowing on the building and heating inside the building [N15]. Other mechanisms, such as changes in barometric pressure and negative pressure caused by mechanical ventilation, may also be significant [N14].

88. Wind creates a negative pressure drop across the shell of a building. The magnitude of the drop is determined by the configuration of the building and varies with the square of the windspeed; in a light breeze, it may be a few pascals [N14]. Outdoor air is therefore drawn inwards through gaps in the shell or through the subjacent earth with radon entrained. The rapidity with which a pressure drop is transmitted depends on the permeability of the ground and can vary from seconds for sand to weeks for clay [N14].

89. Heat also creates a pressure drop across the shell of the building with the gradient towards the higher temperature. This phenomenon, usually called the stack effect, also draws air through and under the shell. The drop is proportional to the temperature differences [F7]; for 20° C, it also amounts to a few pascals. In severe climates, however, it would be much more and in tropical climates much less. The overall effect of both mechanisms is assumed to create a pressure difference, Δp, of about 5 Pa [R4].

90. If a masonry floor is intact, advection from the earth cannot take place. The presence of cracks in the element allows advection, however, and a mathematical model has been used to determine the influx of radon [D7]. As with diffusion through cracks [D6], the finite difference method is used to solve numerically the steady-state transport equation for advection. Apart from Δp, the parameter of prime importance is the permeability, k, of the subjacent earth material, which varies in value through several orders of magnitude from a low of 10^{-16} m^2 for fine clay to a high of 10^{-8} m^2 for coarse gravel [N14].

91. Application of the model to a floor element with an array, as before, of 1 cm wide cracks every 1 m, yields ratios between the advective and diffusive influxes for a range of permeabilities [W8]. These ratios vary from about unity at lower permeabilities to an order of magnitude greater when k is about 10^{-10} m^2 and then decline towards unity again at higher permeabilities. Extension of the model to a bare earth floor yields estimates of influx for lower and intermediate permeabilities, but the method breaks down at higher permeabilities. When these results are applied to the model building for an underpressure of 5 Pa, they give the flux densities in Table 20, which are averaged over the whole area of the floor. They should be compared to the diffusive flux densities of 0.0052 Bq m^{-2} s^{-1} for the cracked floor and 0.026 Bq m^{-2} s^{-1} for the bare earth estimated earlier. Values of the flux density similar to those shown in this Table would be obtained for similar values of the product $k\Delta p$ within the underpressure range 1-10 Pa [D7].

92. Radon entry rates by advection are calculated from equation (7) by again substituting S_E = 100 m^2 for S_B and by replacing the diffusive flux density by the advective values in Table 20. The outcome is also shown in Table 20. Entry rates vary from zero for an impermeable floor element, through 10 Bq m^{-3} h^{-1} for a cracked floor on earth material of low permeability, to 274 Bq m^{-3} h^{-1} for a bare floor of fairly high permeability. The decline in rates at the higher

permeabilities is due to the depletion of radon in the earth near the walls of the building by the passage of fresh air [D7, W8]. If an intermediate permeability of 10^{-11} m^2 for sandy-silty earth material is deemed to be typical and accordant with the diffusion coefficient adopted earlier, it becomes clear from the Table and from the earlier paragraphs that advection is likely to dominate over diffusion as a source of radon in buildings under common circumstances.

93. It is possible to estimate an upper value of the entry rate by advection from the earth in a simple manner if the fraction ϕ is known of the air exchange rate for the building that takes place through the earth. It is given by the expression

$$U = \phi \lambda_v [(C_{Ra} f \rho)/\varepsilon] \qquad (8)$$

where λ_v is the air exchange rate (1 h^{-1}) and the other symbols represent the same quantities as before with the same values. The terms in brackets refer to the radon concentration in equilibrium with radium at depth in the earth; their conjoint value is about $5\ 10^4$ Bq m^{-3}. A value of 0.02% for ϕ would yield an entry rate of 10 Bq m^{-3} h^{-1} for the model building and thus match the contribution by diffusion from the building elements. Values of ϕ two orders of magnitude greater may be realized [S21] for solid floors on the earth, sometimes called slab on grade. This simple analysis does not, however, take into account the depletion of radon near the surface of the earth.

94. It must be stressed that entry by advection is quite dependent on the configuration of the floor and that any estimate of an illustrative value is quite uncertain. Even for the simple slab on grade of the model building, structural details and the nature of the underfill make estimating difficult. For suspended floors, entry is severely influenced by the degree to which the living space is decoupled from the earth. For buildings with basements, the difficulty is compounded by the extensive area of contact between the structural elements and the backfill or earth. Much still remains to be done to clarify these issues [G10, H15, M22, N16, R4], and it must be realized that reliable estimates of indoor radon concentrations are best obtained from measurements of radon in air.

4. Infiltration

95. Fresh air enters a building through open doors, windows and ventilators and through inadvertent gaps in the superficial shell. Although the term infiltration properly refers to the passage of air through small openings, it is used here to describe the overall degree of direct exchange between outdoor and indoor air. Outside air brings with it radon, usually at a low concentration.

96. Concentrations of radon outdoors are determined by the flux density from the earth and by dispersion in the atmosphere; both are affected by meteorological conditions. There are pronounced diurnal variations, mainly because of changes in atmospheric stability, and pronounced seasonal variations, mainly because of changes in patterns of air mass circulation. Water masses such as lakes and oceans make a negligible contribution to the atmospheric inventory of radon [N17]. On the basis of exhalation data, NCRP [N2] estimated the average outdoor concentration over continents to be 8 Bq m^{-3}. Hourly measurements over several years at an inland and a coastal site in the United States yielded average values of 8 and 4 Bq m^{-3} [F8], respectively, but successive quarterly measurements with integrating devices nationwide at 50 sites gave 15 Bq m^{-3} [H16]. Year-long measurements with integrating detectors throughout the United Kingdom gave a population-weighted average of 4 Bq m^{-3} [W3]. Integrating devices deployed in an urban area of Japan also yielded a year-long average of about 4 Bq m^{-3}, with seasonal variations from 2.6 to 6.1 Bq m^{-3} [M23]. Summertime measurements across Canada gave 11 Bq m^{-3} in the eastern provinces and 56 Bq m^{-3} in the prairie provinces, which were particularly dry and where the levels were reduced by a factor of 5 in the following summer [G11]. Protracted measurements in France showed 60 Bq m^{-3} in sedimentary regions, with marked temporal and spatial variations throughout the country [R15]. Whereas a tentative estimate of 5 Bq m^{-3} was made for the population-weighted parameter worldwide in the UNSCEAR 1988 Report [U1], the developing evidence, especially for continental as opposed to island air, suggests that it is probably closer to 10 Bq m^{-3}.

97. With a direct air exchange rate, λ_v, of 1 h^{-1} and an outdoor concentration, χ, of 10 Bq m^{-3}, the rate of entry of radon to the reference building by infiltration is the product of the two values, 10 Bq m^{-3} h^{-1}.

5. Transfer from water and natural gas

98. As noted earlier, radon is soluble in water. It follows that water supplies bring radon indoors and that some de-emanation of the water occurs, thus contributing to the radon entry rate, sometimes to an appreciable degree. Concentrations of radon in water vary markedly. Supplies may be classified broadly as surface water, groundwater or well water. As shown in Table 21, radon concentrations in these classes differ by an order of magnitude, and utilization also varies considerably [N18, O5]. Surface waters with the

least radon but the greatest variability in concentration [H5, H6, N15] are used the most. The weighted average of the radon concentrations for the reference set of supplies is somewhat above 10,000 Bq m^{-3} but not unlike the estimate for the United States [C8]. In the UNSCEAR 1988 Report [U1], a reference value of 1,000 Bq m^{-3} was adopted, but it was noted that countries such as Finland and Sweden had population-weighted averages of over 30,000 Bq m^{-3} [K4, S15]. Comprehensive surveys of well water from southern Finland yielded a median concentration of 210,000 Bq m^{-3} and isolated values approaching 50 MBq m^{-3} [J8]. It is assumed in this Annex that the worldwide average concentration of radon in water is 10,000 Bq m^{-3}.

99. Radon is slowly removed from still water by molecular diffusion, but agitation and heating cause water to de-emanate rapidly and transfer the gas to the indoor air. The transfer factor for buildings, defined as the ratio of the concentrations of radon in water and air, has been determined both experimentally and analytically. Values are distributed log-normally, but the average is about 10^4. For 10,000 Bq m^{-3} in water, this implies 1 Bq m^{-3} in air; for an air exchange rate of 1 h^{-1}, this implies a radon entry rate of 1 Bq m^{-3} h^{-1} to the model building.

100. In the interest of completeness, natural gas is mentioned as a potential source of radon. It contains various concentrations of the radioactive species, determined mainly by the geology of the gas field and the delay in transmission to the user. When it is burned indoors, the radon is released. In the UNSCEAR 1988 Report [U1], an entry rate of 0.3 Bq m^{-3} h^{-1} to the model building was deemed appropriate. This estimate still seems to remain valid.

6. Entry rates

(a) Radon

101. Radon entry rates for the model building are summarized in Table 22, and the relative importance of the various sources of radon in a temperate climate is illustrated. It will be recognized from the preceding text that the selection of illustrative values is rather arbitrary, since it depends on the values chosen for the parameters that determine the significance of the various mechanisms of entry. Nevertheless, the overall entry rate is not greatly at variance with that inferred from radon measurements in many buildings in temperate climates. With a contribution of over 50%, mostly from forced advection through discontinuities in the floor, radon entry from the subjacent earth dominates over all other sources. Diffusion from the building elements is also important, as is the infiltration of outdoor air, but the other sources are relatively unimportant. Table 22 focuses attention on the importance of advection in such typical circumstances; the text emphasizes its importance in atypical circumstances where high radon levels occur indoors. In tall blocks of dwellings, however, the earth contribution would virtually disappear the overall entry rate would at least be halved, and the percentages would be altered accordingly.

102. If a building with dimensions similar to those of the model but of non-masonry construction is envisaged for a tropical climate, it is possible to estimate the entry rate of radon by crudely adjusting the data in Table 22. Diffusion from building elements virtually disappears, but diffusion from the subjacent earth may contribute 37 Bq m^{-3} h^{-1} because board floors would not appreciably impede the ingress of radon. Advection from the earth may also disappear with calm air, balanced temperature and high ventilation. On the other hand, the contribution from infiltration would increase twofold, to 20 Bq m^{-3} h^{-1}, with a direct air exchange rate of 2 h^{-1}. The other mechanisms would remain unimportant. Overall, therefore, the entry rate of radon under such conditions should not be much different from that in Table 22, although the individual percentages would change.

(b) Thoron

103. There is less information on entry rates of thoron into buildings. Since the precursors of ^{220}Rn and ^{222}Rn have about equal activities in earth and building materials (see Tables 5, 6, 17 and 18), the rates at which the two isotopes are produced are also about equal. It is usually assumed that the emanation fraction is the same for each.

104. By definition, the diffusion coefficient is the same for both isotopes, so the diffusive flux density in terms of activity is proportional to the square root of the decay constants (0.0126 s^{-1} for thoron and 2.1 10^{-6} s^{-1} for radon) implying a value 77 times higher for thoron. The measured values for thoron, about 1 Bq m^{-2} s^{-1} from earth materials and 0.05 Bq m^{-2} s^{-1} from building materials [D11, F6, N19, S19, S36, U3], reflect this ratio, although there is considerable variability in the value.

105. As for advection, the flux density should, in principle, be the same for both isotopes in materials with the same permeability, if all the atoms produced are forced to the surface [N19]. Overall, the rate of entry of thoron into a building with unfinished walls and floors is likely to appreciably exceed that of radon. However, owing to its short half-life of 55 seconds, only the superficial layers of walls and floors contribute to the rate of entry of thoron into a

building, so that covering the floors and walls with plastic materials, tiles or paint is likely to reduce the rate of entry of thoron by at least an order of magnitude. This effect was indirectly demonstrated in Japan, where indoor measurements generally detected high concentrations of thoron (up to 400 Bq m^{-3}) near unfinished soil walls, but no thoron near walls covered by plastic or by paint [D2].

106. From the relatively few measurements of thoron outdoors [N19, S23, U3] it would appear that activity concentrations of thoron at or very near the surface of the earth exceed those of radon. As altitude increases, however, the situation reverses because of the disparity in decay constants. A representative value of 10 Bq m^{-3} might be chosen for head height, which is the same as the value adopted earlier for radon. With a direct exchange rate between outdoor and indoor air of 1 h^{-1}, the rate of entry to the model building by infiltration is also about 10 Bq m^{-3} h^{-1}.

107. The average rate of entry of thoron to a building from all mechanisms is crudely estimated in this Annex to be similar to that of radon, i.e. about 50 Bq m^{-3} h^{-1}. This estimate is highly uncertain.

B. EXPOSURE

1. Indoor concentrations

(a) Radon

108. It is possible to estimate the activity concentration χ (Bq m^{-3}) for the model building from the expression

$$\chi = U/(\lambda_v + \lambda_{Rn}) \qquad (9)$$

where the symbols refer to quantities defined previously. With U (the radon entry rate) = 49 Bq m^{-3} h^{-1} (Table 22), λ_v = 1 h^{-1} and λ_{Rn} = 0.00756 h^{-1}, the value of χ is 48.6 Bq m^{-3}. In round terms, therefore, one would generally expect radon gas concentrations of about 50 Bq m^{-3} in masonry buildings in temperate climates and 30 Bq m^{-3} in tropical timber buildings. With thoron, however, the decay constant of 45.4 h^{-1}, rather than the air exchange rate, determines the concentration: for U = 50 Bq m^{-3} h^{-1}, χ = 1 Bq m^{-3} of thoron gas. It should be noted that the indoor radon and thoron concentrations calculated from equation 9 represent averages throughout the building. Because of its short half-life, thoron does not become uniformly distributed. Strong gradients of thoron concentration have been predicted and observed according to distance from the wall [D2, D9, K15]. In any case, because of the large uncertainties in the estimation of the rate of entry of thoron into buildings, it is not recommended to use equation 9 to predict the indoor thoron concentration; it is better to rely on direct measurements of indoor concentrations, discussed in Section III.B.1.b.

109. It is now appropriate to compare expectation with observation. Although most large surveys are of radon gas concentration, χ_{Rn}, some surveys have been conducted of the decay products. The parameter of interest in the latter case is the equilibrium equivalent concentration (EEC) of radon χ_{Eq}, and the two quantities are related through the equilibrium factor F, defined by the expression

$$F = \chi_{Eq}/\chi_{Rn} \qquad (10)$$

where χ_{Eq} is $0.105\chi_1 + 0.515\chi_2 + 0.380\chi_3$. The symbols χ_1, χ_2 and χ_3 represent the activity concentrations of ^{218}Po, ^{214}Pb and ^{214}Bi; the constants are the fractional contributions of each decay product to the total potential alpha energy from the decay of unit activity of the gas [I7]. By analogy, the equilibrium equivalent concentration of thoron is $0.913\ \chi_1 + 0.087\ \chi_2$, where χ_1 and χ_2 now represent the activity concentrations of ^{212}Pb and ^{212}Bi.

110. Many surveys have been made during the last decade of radon concentrations in dwellings. An extensive compilation was included in the UNSCEAR 1988 Report [U1]; it is updated here by the information in Table 23. Data are now available for 35 countries representing almost two thirds of the world population. The list is not comprehensive; some scattered observations for other countries are omitted, and summary results for a few countries with advanced radon programmes may not have been available. The purpose here is not to record all such data, but to select information that is representative of the various countries. The distribution of the survey data of Table 23 is illustrated in Figure IV.

111. Whereas early surveys were based on discrete sampling of radon decay products, usually called grab sampling, because it lasted a matter of minutes, surveys of substance are now made by sampling radon gas for extended periods of time, several days for charcoal detectors and several months for track etch detectors. Mass surveys of radon decay products are not feasible because the equipment and human resources required to conduct them would be very costly.

112. A satisfactory national survey might be defined as one in which measurements of adequate quality are made throughout a year in the living and sleeping rooms of a stratified sample of at least 1 in 10,000 of the housing stock. Not many surveys meet these criteria. Some are not large enough; many are made in the rooms with the highest radon levels; some are

biased to areas of the country with high radon concentrations; most do not follow a statistical design. As a result, any estimate of a representative or typical world value is quite uncertain. Distributions of radon concentrations are usually reported as being log-normal, although departures are sometimes seen. Arithmetic means are frequently cited or may be calculated from the geometric mean and standard deviation. Extreme values are often given.

113. Owing to the large populations of China and India, the results for these countries weigh heavily in the estimation of a worldwide radon concentration. Definitive national surveys have not yet been conducted, but the population-weighted mean of somewhat disparate and developing data for China [C10, R5, U1, Z2] is about 20 Bq m^{-3} [P21]. Exploratory data for India [S37], pending the completion of a national survey, suggest an arithmetic mean of 57 Bq m^{-3}, with lower values in cities such as Bombay [M12] and higher values in cities such as Nagpur [S24] and an equilibrium factor approaching 0.4 [S25]. A national residential radon survey [M24, O10, U12] recently completed in the United States yielded an arithmetic mean of 46 Bq m^{-3}, which is consistent with the outcome of a structured survey in the state of New York [P11].

114. Results from several studies in southern Europe have become available. Generally radon values are lower than in northern Europe: for example, only 3.2% of the 244 Spanish dwellings investigated in Madrid and Barcelona exceeded 200 Bq m^{-3} [G1]; only about 20% were above 100 Bq m^{-3} in a Turkish survey of 400 houses in Istanbul [K14]; and about 5% of Portuguese dwellings had average radon concentrations in excess of 200 Bq m^{-3} [F14]. However, in Italy the use of natural building materials (tuffs, pozzuolana) with elevated ^{238}U activity concentrations ranging up to 400 Bq kg^{-1} can result in elevated indoor radon levels in the areas concerned (arithmetic average: 93 Bq m^{-3} [B16]). Frequently, seasonal changes are seen to have a pronounced effect on indoor radon concentrations in southern climates, with winter values up to 80% higher than corresponding summer values [B16, G1].

115. Little information is available for large parts of Africa and for tropical regions in the Americas, Asia and Oceania. For well-ventilated buildings, indoor and outdoor radon concentrations should be essentially equal; thus, indoor radon levels should be lower in tropical areas than in temperate areas if the outdoor radon concentrations are similar [M12, S25]. The limited results available for Egypt and Thailand [C23, H18] show that, for well-ventilated buildings in tropical areas, indoor radon concentrations are approximately equal to those measured outdoors; furthermore, a gradual increase in the ratio of indoor-to-outdoor radon concentration from low latitudes (23° N) to temperate latitudes (40° N) has been observed in China [P21]. However, Figure V, where the average indoor radon concentrations from Table 23 are plotted against the latitude of the countries or the main population centres, shows a considerable scatter, as well as some average indoor radon concentrations at high latitudes that are similar to those at low latitudes.

116. The different results of radon concentrations with latitude may be due to local geology, atmospheric conditions or building design. Local geology and atmospheric conditions may result in outdoor radon levels that are high in low latitudes and low in high latitudes. For example, the average outdoor radon concentration measured in Bangkok [C23] is 40 Bq m^{-3}, while that in the United Kingdom is 4 Bq m^{-3} [W3]. Such a difference alters the indoor-to-outdoor concentration ratio for most dwellings. Also, the sharply contrasted rainy and dry seasons in tropical areas may influence the annual average of the indoor radon concentration in a manner that is not clearly understood. Finally, the design of traditional sub-Saharan houses explains the relatively high radon concentrations in that region [O6].

117. In the UNSCEAR 1988 Report [U1], a population-weighted value of 40 Bq m^{-3} was adopted for the arithmetic mean worldwide. This value still appears to be representative. Given the gross uncertainty in this value and the climatic complications, the degree of agreement with the estimate for the model building is probably more coincidental than conclusive. It is clear that additional research and measurements are needed in tropical areas in order to estimate more accurately the worldwide average of indoor radon concentration. It is hoped that more data from countries at low latitudes will become available from a radon survey programme that is being initiated by IAEA [S22].

118. Because of the trend away from the measurement of radon decay products, there is no new information of substance on the value of the equilibrium factor F indoors; it is taken, as before, to be 0.4 [U1]. The position is much the same for outdoor air; the previous value of 0.8 is also adopted here. In terms of equilibrium equivalent concentration, therefore, the worldwide values of the arithmetic mean, population-weighted, are about 16 Bq m^{-3} indoors and 8 Bq m^{-3} outdoors.

119. For the major surveys in temperate climates, the value of the geometric standard deviation is typically 2.5. This may be somewhat high for tropical climates, but any adjustment would be arbitrary, and so it is considered to be generally valid. The arithmetic mean of the radon gas concentration is 40 Bq m^{-3}, and the

geometric mean is about 26 Bq m^{-3}. The corresponding values of the equilibrium equivalent concentration are 16 Bq m^{-3} indoors (arithmetic mean) and 10 Bq m^{-3} (geometric mean). Estimates of the 98th percentiles are 200 Bq m^{-3} for the radon gas concentration and 80 Bq m^{-3} for the equilibrium equivalent concentration. It can thus be suggested that about 2% of dwellings worldwide may have concentrations in excess of these values. Further, about 0.02% of dwellings may be in excess of 800 Bq m^{-3}. Concentrations far in excess of 800 Bq m^{-3} are, however, frequently reported in the literature; values more than an order of magnitude greater are sometimes encountered, which may reflect the possibility of positive divergence from a log-normal distribution at higher concentrations [N20]. Competent authorities who have considered the effects of human exposure to radon in homes are generally agreed on the desirability of taking action at concentrations exceeding 400 Bq m^{-3} [O8]; worldwide, a few homes in a thousand probably exceed that level. Remedial measures in those houses will reduce the number of persons exposed to high doses from the inhalation of radon progeny but it will not change significantly the average levels.

(b) Thoron

120. Limited information on thoron concentrations has been reported since the publication of the UNSCEAR 1988 Report [U1]. A representative value of 10 Bq m^{-3} was adopted earlier for thoron gas in outdoor air. Equilibrium equivalent concentrations of about 0.1 Bq m^{-3} have been adopted elsewhere [N2, N19, N20], somewhat lower than the previous value of 0.2 Bq m^{-3} [U1]. Estimates of the gas concentration indoors point to around 3 Bq m^{-3} [N20, S23], and limited surveys of the equilibrium equivalent concentration [C16, D8, G9, M14, M25, N19, P21, R1, S23, T7, W3], taken together, indicate about 0.3 Bq m^{-3}, again somewhat lower than the previous value of 0.5 Bq m^{-3} [U1]. There is considerable uncertainty in these figures, pointing to a need for systematic measurements.

(c) Average concentrations

121. The foregoing estimates of the concentrations of radon and thoron in outdoor and indoor air are summarized in Table 24. Both the gas and equilibrium equivalent values are given. They are intended to represent the population-weighted arithmetic means worldwide, but it is necessary to bear in mind that considerable uncertainty attaches to them, mainly because of the general paucity of data for thoron and some geographical bias in the origins of the radon data. They are, nevertheless, robust and round enough to allow calculating the radiation doses from inhalation for the gas and decay products.

2. Dose

(a) Inhalation

122. Exposure to radon, thoron and their progeny comes mainly from the inhalation of the decay products of radon and thoron, which deposit inhomogeneously within the human respiratory tract and irradiate the bronchial epithelium. Compared with the lung dose from inhaled decay products, the dose contribution from the inhaled radon (or thoron) gas itself, which is soluble in body fluids and tissues, is small under normal conditions of exposure. The two contributions to the annual effective dose are considered in turn.

123. Conversion coefficients relating average annual concentrations to effective dose equivalent were presented in the UNSCEAR 1988 Report [U1] for radon and thoron progeny. These were based mainly on a comprehensive report on lung dosimetry published in 1983 [N21] and other earlier analyses [I7, J3]. Parallel and later developments were recognized, however, that pointed to the need for a re-evaluation of the radon dosimetry [J4, N17, V4].

124. Dose to lung tissues depends, among other things, on the fraction f_p of the total potential alpha energy associated with the mixture of decay products not attached to the ambient aerosol [N21]; as the value of f_p increases, so does the dose. Values from 0.04 to about 0.20 have been found in several dwellings in the United Kingdom [J5, S27]. A similar range was determined in several Norwegian dwellings [S28]. For a Japanese dwelling, however, the range was 0.031 to 0.064, with an arithmetic mean of 0.043 [K6], reflecting perhaps the different lifestyle [H8]. In Germany, the arithmetic mean for many rooms without additional aerosol sources was 0.096, whereas for a few with cigarette smoke it was 0.006 and for outside air, about 0.02 [R9]. A study in a test dwelling in Germany yielded values around 0.1, but ranging below 0.01 as a result of smoking [R10]. A review of these and other data leads to a value of around 0.1 [P16]. Further results reveal 0.077 [H21] and 0.20 [S46] for single-family dwellings and 0.086 as an average for five dwellings [T13]. Such values may be contrasted with those from 0.02 to 0.03, adopted previously for dosimetric purposes [I8, N21, U1]; they appear to be about three times greater indoors, the implication being that the equivalent dose to the bronchial epithelium might be somewhat larger than previously estimated [J11].

125. The rate of attachment of radon decay products to the ambient aerosol increases as the aerosol concentration increases [P12]. With other aerosol conditions constant, therefore, a higher aerosol

concentration means a lower value of f_p and a lower dose. In dwellings, the aerosol concentration generally increases as the infiltration rate of outside air decreases, with the result that the values of f_p and dose also decrease. For a given concentration of gas at a fixed value of f_p, the dose increases as the value of the equilibrium factor F increases; the value of F, however, increases with decreasing infiltration rate. The effects of f_p and F on dose, with other aerosol conditions constant, are therefore counterbalanced.

126. Concurrent measurements of f_p and F [J5, P13, R9, R10, S28] demonstrate that values of f_p are negatively correlated with values of F. Concurrent measurements of decay product concentrations, infiltration rates and size distributions of ambient aerosols in rooms [V4, V5] and the use of a room model [P14] to estimate the value of the unattached fraction also substantiated the inverse relationship between f_p and F [P16]. Further calculations of doses to lung tissues with two reference dosimetry models [N21] showed that the gas concentration was an adequate indicator of effective dose equivalent; a conversion coefficient of around 50 μSv a^{-1} per Bq m^{-3} of radon gas was deemed appropriate [V5]. A similar conclusion had been reached in an earlier assessment [J5] and was supported by a later analysis [H9]. On the other hand, a more recent assessment indicates that the coefficient may be around 25 μSv a^{-1} per Bq m^{-3} [J10]. Given the preponderance of radon gas measurements as opposed to decay product measurements in surveys of dwellings, there is some merit and much convenience in applying such a conversion coefficient directly to the results, but unanimity is lacking on the most appropriate value to use.

127. The dosimetry of radon and decay products is under review to account for the introduction of the new ICRP recommendations [I6] and to develop a new dosimetric model for the respiratory tract [B2]. Dosimetrists are considering new physical information on the indoor aerosol, new insights into the regional sensitivity of the respiratory tract and the new tissue weighting factors.

128. For the purposes of this Annex, it seems reasonable to keep the dose coefficients that were adopted in the UNSCEAR 1988 Report. In that Report, an indoor exposure to radon at a concentration of 40 Bq m^{-3} was estimated to correspond to an annual effective dose equivalent of 1.0 mSv as a result of the irradiation of tissues of the respiratory tract by the radon progeny. This is numerically equivalent to an effective dose coefficient of 25 μSv a^{-1} per Bq m^{-3} of radon gas for indoor exposure, assuming an occupancy factor of 0.8 (7,000 hours spent indoors in a year), or to 3.6 nSv per Bq h m^{-3} of radon gas.

129. When the effective dose coefficient is expressed in terms of equilibrium equivalent concentration (EEC) of radon, the result is slightly different from that adopted in the UNSCEAR 1988 Report, because the EEC of radon is estimated in this Annex to be 16 Bq m^{-3} instead of 15 Bq m^{-3}, as in the earlier Report, the radon gas concentrations being the same. Expressed in terms of the EEC of radon, the effective dose coefficient is found to be $3.6 \times 40 \div 16 = 9$ nSv per Bq h m^{-3} for EEC of radon instead of 10 nSv per Bq h m^{-3}, as in the UNSCEAR 1988 Report. The value 9 nSv per Bq h m^{-3} for EEC of radon is also used in this Annex to estimate effective doses resulting from the inhalation of radon progeny outdoors.

130. It is convenient at this point to consider the doses from the inhalation of radon gas in somewhat more detail. Since the gas is soluble in body fluids and tissues, it is transported throughout the body. Doses are delivered from the decay of the gas itself and the short-lived decay products. Equivalent dose rates to some tissues of interest from constant inhalation of the gases at concentrations of 1 Bq m^{-3} are 1.2 nSv h^{-1} in fat, 0.75 nSv h^{-1} in lungs and 0.094 nSv h^{-1} in bone marrow from radon and 0.004 nSv h^{-1} in fat, 0.58 nSv h^{-1} in lungs and 0.039 nSv h^{-1} in bone marrow from thoron [J3]. The effective dose rates are 0.17 nSv h^{-1} from radon and 0.11 nSv h^{-1} from thoron. The resulting annual effective doses per unit concentration in air are 1.5 μSv per Bq m^{-3} of radon and 0.96 μSv per Bq m^{-3} of thoron. These values are supported by a more recent assessment [P15]. The relatively high dose rate from radon in fatty tissue is due to the high solubility of radon. In an earlier investigation [H10], the distinction was made between fatty and normal marrow; the ratio of the dose rates was about 5. From these dose coefficients it may be estimated that the equivalent dose to the marrow from the worldwide average value of radon and thoron is about 0.03 mSv a^{-1}, an order of magnitude less than the equivalent dose from cosmic rays.

131. The dose coefficients corresponding to the inhalation of the thoron progeny are taken to be the same as those adopted in the UNSCEAR 1988 Report, namely 10 nSv per Bq h m^{-3} for outdoor exposure and 32 nSv per Bq h m^{-3} for indoor exposure.

132. The effective dose coefficients related to the inhalation of radon gas, thoron gas, radon progeny and thoron progeny are summarized in Table 24. Annual effective doses corresponding to the worldwide average concentrations are estimated from those effective dose coefficients, assuming average occupancy factors of 0.2 for outdoors and 0.8 for indoors; the results are included in Table 24. The average annual effective dose from inhalation of radon and its progeny is estimated to be 1200 μSv, while the dose from thoron and its progeny is about 70 μSv.

(b) Ingestion

133. When internal exposures were considered in Section II.B, the dose from the ingestion of radon in water was not included. These doses are estimated here. Application of a modified ICRP model to the ingestion of radon in water [K7] leads to a value of 10^{-8} Sv Bq^{-1} for the committed effective dose per unit intake, with virtually all of the dose coming from the gas rather than the decay products. Doses to children and infants, scaled from body masses, are 2 10^{-8} Sv Bq^{-1} and 7 10^{-8} Sv Bq^{-1}, respectively. Since radon is readily lost from water by heating and bottling, the consumption of interest here is that of water directly from the tap. Annual intakes by adults and children are about 50 l and 75 l, with 100 l by infants when scaled by metabolic rate [I5]. The estimate for adults is supported by other statistics [H11]. For the reference concentration of 10,000 Bq m^{-3} adopted earlier, the annual effective doses are 5 μSv to adults, 15 μSv to children and 70 μSv to infants. Assuming that a representative population consists of 5% infants, 30% children and 65% adults, the population-weighted average annual effective dose from ingestion of radon is about 10 μSv, which is small in comparison to doses from the inhalation of radon or thoron progeny. However, persons who consume deep well waters with the reference concentration of 10^5 Bq m^{-3} will incur doses an order of magnitude greater. This gives an indication of the range experienced by communities with atypical supplies.

C. SUMMARY

134. Radon and its decay products make the most significant contribution to exposures from natural radiation. In particular, levels indoors can build up following entry from subjacent soil, building materials and the infiltration of outdoor air. Extensive national surveys have been conducted to determine both typical and extreme levels in houses.

135. The population-weighted average radon concentration is 40 Bq m^{-3} indoors. Most of the data are from temperate regions. Average levels outdoors are 10 Bq m^{-3} in continental areas and somewhat less in coastal regions. Levels indoors in tropical regions should be comparable to outdoor levels in consideration of construction materials and probable ventilation, but more data are needed to substantiate this. The equilibrium factors to determine equilibrium equivalent concentrations (EEC) are taken to be 0.4 for indoor exposure and 0.8 for outdoor exposure. The population-weighted average EEC radon concentra-tions are therefore estimated to be 16 Bq m^{-3} indoors and 8 Bq m^{-3} outdoors.

136. The dosimetry of radon and its decay products is at present under review, and uncertainty prevails about a conversion coefficient suitable for deriving the effective dose from the concentration. In this Annex, the effective dose coefficient that was adopted in the UNSCEAR 1988 Report for inhalation of radon progeny has been kept; in numerical terms, the effective dose from 1 Bq h m^{-3} radon EEC is estimated to be 9 nSv for both indoor and outdoor exposures. The average annual effective dose from the inhalation of radon progeny outdoors is estimated to be 8 Bq m^{-3} (EEC) × 9 nSv h^{-1} per Bq m^{-3} (EEC) × 0.2 (occupancy) × 8760 h a^{-1} = 0.13 mSv. For radon indoors, it is 16 Bq m^{-3} (EEC) × 9 nSv h^{-1} per Bq m^{-3} (EEC) × 0.8 × 8760 h a^{-1} = 1.0 mSv. The dose from inhaled radon that becomes dissolved in tissues is estimated to be [(10 Bq m^{-3} × 0.2) + (40 Bq m^{-3} x 0.8)] × 1.5 μSv a^{-1} per Bq m^{-3} = 0.051 mSv. Thus, the total estimated average annual effective dose is 1.2 mSv. The corresponding annual effective dose from inhalation of thoron and its decay products is 0.07 mSv. An additional annual effective dose to adults of 0.005 mSv is estimated to result from ingestion of radon.

IV. EXTRACTIVE INDUSTRIES

137. The extraction and processing of earth materials affect exposure to natural radiation of the general public when these earth materials, or their industrial products or by-products, contain above-average concentrations of natural radionuclides. The earth materials that are considered in this Annex exclude uranium, which is discussed in Annex B, "Exposures from man-made sources of radiation". In the industrial processes associated with the extraction and processing of earth materials, the hazard from radiation is generally small compared to that from other chemical substances, so radiation is not systematically monitored. The assessment of such exposures is based on sketchy information derived from isolated surveys. This Chapter reviews the information available on radiation exposures from four types of activity: (a) combustion of coal; (b) other energy production from fossil fuels; (c) use of phosphate rock; and (d) mining and milling of mineral sands. Except for the Section on mining and milling of mineral sands, this Chapter essentially summarizes the review presented in the UNSCEAR 1988 Report [U1], as very little new

information has since been published. Collective effective doses committed from atmospheric discharges of radioactive materials are estimated using the crude models described in the UNSCEAR 1982 Report [U3].

138. In order to allow their comparison with the doses from natural radiation background, the annual per caput effective doses resulting from the extraction and processing of earth materials have been estimated. In doing so, crude assumptions have been made about the dynamics of the dose rate and the duration of the practice considered. It is emphasized that all estimates of dose resulting from the extraction and processing of earth materials are fraught with large uncertainties.

A. ENERGY PRODUCTION FROM COAL

139. The world production of coal, expressed in coal equivalent for energy purposes, was 3.1×10^{12} kg in 1985, the main producers being China, the republics of the former Soviet Union and the United States [U13]. A large fraction of the coal extracted from the earth is burned in electric power stations; about 3×10^9 kg of coal is required to produce 1 GW a of electrical energy. In the UNSCEAR 1982 Report [U3], the Committee estimated the average concentrations of ^{40}K, ^{238}U and ^{232}Th in coal to be 50, 20, 20 Bq kg^{-1}, respectively, based on the analysis of coal samples from 15 countries, and noted that the concentrations varied by more than two orders of magnitude. The results of an extensive survey of coal from China, which produces 20% of the world's total, point to concentrations that are appreciably higher: 104, 36 and 30 Bq kg^{-1} for ^{40}K, ^{238}U and ^{232}Th, respectively [P22]. The higher concentrations of natural radionuclides in coal from China do not result in substantial increases in the worldwide averages, which are little more than educated guesses, but they do allow a better assessment of the doses due to the uses of coal in China. Radiation exposures occur throughout the fuel cycle, which consists of coal mining, the use of coal and the use of fuel ash.

1. Coal mining

140. Members of the public are exposed to the radon present in the exhaust air of coal mines. Since there are currently no measured data on the emission of radon from coal mines, the Committee, in the UNSCEAR 1988 Report [U1], used two different, very crude approaches to estimating the annual releases of radon from coal mining all over the world; the figures obtained were 30 and 800 TBq, leading to collective effective doses per year of practice of 0.5 and 10 man Sv, respectively. Dividing by the world population of $5.3\ 10^9$ yields an annual per caput effective dose of 0.1-2 nSv.

2. Use of coal

141. There are vast differences in the relative use of coal in various countries. In the OECD countries, which account for about one third of the world's coal production, 68% of the coal produced is burned in electric power stations, 30% in coke ovens and other industrial operations and 2% in dwellings [U13]. In China, 25% of the coal produced is burned in electric power stations, 59% in other industries and 16% in dwellings [P23]. Assuming that the usage distribution of coal in China is representative of the distribution in countries that are not members of the OECD, the average worldwide usage of coal is as follows: about 40% is burned in electric power stations, 10% in dwellings and 50% in other industries. When coal is burnt, the naturally occurring radionuclides are redistributed from underground into the biosphere. The resultant doses from burning coal in power stations and in dwellings are considered below. There is not enough information on the releases of radionuclides from burning coal in other industries to assess this use of coal.

(a) Coal-fired power plants

142. Coal is burned in furnaces operating at up to 1,700° C in order to produce electrical energy. In the combustion process, most of the mineral matter in the coal is fused into a vitrified ash. A portion of the heavier ash, together with incompletely burned organic matter, drops to the bottom of the furnace as bottom ash or slag. The lighter fly ash, however, is carried through the boiler, together with the hot flue gases and any volatilized mineral compounds, to the stack, where, depending on the efficiency of emission control devices, most is collected while the rest (escaping fly ash) is released to the atmosphere. Owing mainly to the elimination of the organic content of the coal, there is approximately an order of magnitude enhancement of the concentrations from coal to ash. Consequently, the natural radionuclide concentrations in ash and slag from coal-fired power stations are significantly higher than the corresponding concentrations in the earth's crust. Arithmetic averages of the reported concentrations in escaping fly ash are 265 Bq kg^{-1} for ^{40}K, 200 Bq kg^{-1} for ^{238}U, 240 Bq kg^{-1} for ^{226}Ra, 930 Bq kg^{-1} for ^{210}Pb, 1,700 Bq kg^{-1} for ^{210}Po, 70 Bq kg^{-1} for ^{232}Th, 110 Bq kg^{-1} for ^{228}Th and 130 Bq kg^{-1} for ^{228}Ra ([U3], Annex C, paragraph 11).

143. The amounts of natural radionuclides discharged to the atmosphere from a power plant depend on a number of factors such as the concentrations in coal,

the ash content of the coal, the temperature of combustion, the partitioning between bottom ash and fly ash and the efficiency of the emission control device. In the UNSCEAR 1988 Report [U1], the Committee estimated the amounts of radioactive materials discharged to the atmosphere for typical old and modern plants. The resulting normalized collective effective doses were 6 and 0.5 man Sv $(GW\ a)^{-1}$ for typical old and modern plants, respectively. Data from China indicate that because of higher-than-average concentrations of natural radionuclides in coal, relatively low filter efficiencies (90%) and high population densities around the plants, the normalized collective effective doses arising from atmospheric releases of radioactive materials from plants there is approximately 50 man Sv $(GW\ a)^{-1}$ [P22]. Assuming that, worldwide, one third of the electrical energy produced by coal-fired power plants is from modern plants, with another third from old plants and the remaining third from plants with characteristics similar to those in China, the average normalized collective effective dose is 20 man Sv $(GW\ a)^{-1}$.

144. According to the dose assessment methodology used in the UNSCEAR 1988 Report, about 70% of the effective dose resulting from atmospheric releases of natural radionuclides from old plants is due to the inhalation of long-lived radionuclides as the cloud passes. The remainder of the effective dose is due to external irradiation from radionuclides deposited on the ground and to the ingestion of foodstuffs contaminated by radionuclides deposited on the ground. It is assumed that the deposited activity becomes unavailable to the vegetation, with a mean life of 100 years for all the natural long-lived radionuclides. On the whole, the effective dose per unit release is delivered at a rate that decreases slowly over a century or so.

145. Assuming that (a) $3\ 10^{12}$ kg of coal is produced in a year; (b) 40% of the coal production is burned in electric power stations; and (c) $3\ 10^{9}$ kg of coal is required to produce 1 GW a of electrical energy, the annual electrical energy produced by burning coal worldwide is 400 GW a. The collective effective dose per year of practice is therefore estimated to be 20 man Sv $(GW\ a)^{-1}$ x 400 GW a = 8,000 man Sv.

146. Crude assumptions are necessary to derive the annual per caput effective dose from the collective effective dose per year of practice. If it is assumed that similar amounts of radioactive materials have been released into the atmosphere by coal-fired power plants year after year for the last century or so, then the collective effective dose per year of practice would be approximately equal to the annual collective effective dose. In fact, coal has been used for about a century to produce electrical energy, but information is lacking regarding the magnitude of the environmental releases during that time. Given the large uncertainty associated with the estimate of the collective effective dose per year of practice, it is assumed in this Annex that the annual collective effective dose has the same numerical value as the collective effective dose per year of practice. The annual per caput effective dose is obtained by dividing the annual collective effective dose (8,000 man Sv) by the current world population ($5.3\ 10^{9}$); the result is about 2 μSv.

(b) Domestic use

147. Another significant use of coal is for domestic cooking and heating. No information has been found in the literature on the environmental discharges of natural radionuclides from this source. The use of coal for cooking or heating in private houses may, however, be estimated to result in high collective doses since chimneys are not equipped with ash removal systems and the population densities around sources of emission are generally high.

148. Assuming that the concentrations in smoke are equal to those in coal and that 3.5% of the coal is emitted as smoke, the annual worldwide atmospheric releases caused by the domestic burning of coal are estimated to be 0.7 TBq of ^{40}K and 0.3 TBq of each of the radionuclides of the ^{238}U and ^{232}Th series (radon and thoron excepted); these figures become 20 times greater if it is assumed that the concentrations in smoke are equal to those in ash and that the coal burned has a 5% ash content. Taking the average population densities around the houses to be $10^{3}\ km^{-2}$ leads to collective effective doses committed from yearly worldwide use of coal in the range of 2,000-40,000 man Sv. This estimate is highly uncertain, as it is not supported by any discharge or environmental data.

149. It is assumed that the annual collective effective dose to the world's population is in the same range as the collective effective dose per year of practice (2,000-40,000 man Sv). It follows that the annual per caput effective dose attributable to the use of coal for domestic cooking and heating would be 0.4-8 μSv.

3. Use of fuel ash

150. Large quantities of coal ash (fly ash and bottom ash combined) are produced each year throughout the world. In the UNSCEAR 1988 Report [U1], the Committee estimated that about 280 million tonnes of coal ash are produced annually in coal-fired power stations. Coal ash is used in a variety of applications, the largest of which is the manufacture of cement and concrete. It is also used as a road stabilizer, as road

fill, in asphalt mix and as fertilizer. Data on the various uses of coal ash in several countries have been reported [G8]. About 5% of the total ash production from coal-burning power stations is used for the construction of dwellings; this represents an annual usage of 14 million tonnes.

151. From the radiological point of view, the use of coal ash in building materials, which may affect indoor doses from external irradiation and the inhalation of radon decay products, is the most significant. With respect to external irradiation, the Committee estimated in the UNSCEAR 1988 Report, on the basis of measurements made by Stranden [S47], that the use of concrete containing fly ash for constructing dwellings would result in additional annual effective doses of 70 μSv and 30 μSv in concrete and wooden houses, respectively. Taking the amount of fly ash concrete to be 1.3 tonnes in a wooden house and 4 tonnes in a concrete building and assuming that an average of four persons live in each house and that the lifetime of the house is 50 years, the collective effective dose arising from external irradiation attributable to the annual use of fly ash for constructing the dwellings is estimated to be about 50,000 man Sv.

152. The annual collective effective dose to the world's population depends on the number of dwellings built with concrete containing coal ash during the last 50 years. Assuming that the practice of building dwellings with concrete containing coal ash began 25 years ago and that 14 million tonnes of coal ash have been used each year for that purpose, the annual collective effective dose to the world's population from external irradiation from that source is half the collective effective dose per year of practice, or 25,000 man Sv. The corresponding annual per caput effective dose is 5 μSv.

153. There are conflicting views on the impact of the use of fly ash on the dose from inhalation of radon decay products. According to some investigators, the indoor dose should be higher in a house with fly ash concrete than in a house built with ordinary concrete [B4, S45]; according to other investigators [S47], the indoor dose should be lower, while another group concluded that there should not be any significant change [U14, V9]. In this Annex, as in the UNSCEAR 1988 Report, it is assumed that the use of fly ash in building materials does not result in any additional dose due to the inhalation of radon decay products.

B. OTHER ENERGY PRODUCTION

154. In addition to the use of coal in power plants to generate electrical energy, other minerals, including oil, peat and natural gas, as well as geothermally heated water, are also used for this purpose. The natural radionuclides in these materials, the amounts released and the resultant doses are considered in this Section.

1. Oil

155. Oil has a large number of fuel applications, the most important being for road transport vehicles, for the generation of electrical energy and for domestic heating. Approximately 3×10^{12} kg of crude petroleum is produced in the world annually. In power plants, about 2×10^{9} kg of oil is needed to produce 1 GW a of electrical energy. As the ash content of oil is very low, oil-fired power plants are usually not equipped with efficient ash removal systems. On the basis of limited measurements, the Committee in the UNSCEAR 1988 Report estimated that the amounts of radioactive materials discharged from oil-fired power plants are similar to those from coal-fired power plants fitted with efficient aerosol control devices; the resulting collective effective dose is about 0.5 man Sv $(GW\ a)^{-1}$. About half of the effective dose results from inhalation during passage of the cloud and the other half from external and internal irradiation from deposited activity. Assuming that 15% of the worldwide production of crude petroleum is burned in electric power plants, the collective effective dose per year of practice is about 100 man Sv. The annual collective effective dose is tentatively estimated to be 50 man Sv, corresponding to an annual per caput effective dose of 10 nSv.

2. Peat

156. Peat is burned to produce energy in several countries, notably in Finland and Sweden [C14]. Concentrations of natural radionuclides in peat are usually similar to those in coal, but relatively high concentrations have been found to occur. In the UNSCEAR 1988 Report, the Committee tentatively estimated the normalized collective effective dose due to atmospheric releases from peat-fired power plants to be 2 man Sv $(GW\ a)^{-1}$. Since no information has been made available to the Committee on the worldwide production of electrical energy by burning peat, the collective effective dose per year of practice has not been estimated.

3. Natural gas

157. Like oil, natural gas has many applications. The main ones are domestic heating, the generation of electrical energy and as a source of heat in various industries. The annual worldwide production of natural gas is about 10^{12} m^3. Radon concentrations in natural gas at the well may vary widely around a typical value of 1 kBq m^{-3}. Owing to radioactive decay during

transfer and storage, the radon concentrations at the plant should be smaller; in the absence of data, however, no decrease has been assumed. Since about 2×10^9 m^3 of natural gas must be burned to produce 1 GW a of electrical energy, the corresponding radon emission is approximately 2 TBq and the normalized collective effective dose is 0.03 man Sv $(GW\ a)^{-1}$. Assuming that 15% of the world production of natural gas is burned in electric power plants, the collective effective dose per year of practice is about 3 man Sv. The annual collective effective dose has the same value, leading to an annual per caput effective dose of about 1 nSv.

4. Geothermal energy

158. Geothermal energy is produced in Iceland, Italy, Japan, New Zealand, the Russian Federation and the United States. Geothermal energy makes use of hot steam or water derived from high-temperature rocks deep inside the earth. Most of the activity found in geothermal fluids is due to the uranium decay chain. Isotopes of solid elements may occur in released water or land-fill, but only radon, which is released into the atmosphere when the water or steam contacts the air, is considered here. From measurements in Italy and in the United States, the Committee, in the UNSCEAR 1988 Report, estimated the average discharge of radon per unit energy generated to be 150 TBq $(GW\ a)^{-1}$ and the corresponding collective effective dose to be 2 man Sv $(GW\ a)^{-1}$. Since the annual production of electrical energy by geothermal energy is about 1.5 GW a, the annual worldwide production of geothermal energy would yield an annual collective effective dose of approximately 3 man Sv and an annual per caput effective dose of about 1 nSv.

C. USE OF PHOSPHATE ROCK

159. Phosphate rock is the starting material for the production of all phosphate products and is the main source of phosphorus for fertilizers. It can be of sedimentary, volcanic or biological origin. The world production of phosphate rock was about 130 million tonnes in 1982, the main producers being China, Morocco, the former Soviet Union and the United States. Concentrations of natural radionuclides in phosphate rock were reviewed in the UNSCEAR 1977 and 1982 Reports [U3, U4]. Concentrations of ^{232}Th and ^{40}K in phosphate rocks of all types are similar to those observed normally in soil, whereas concentrations of ^{238}U and its decay products tend to be elevated in phosphate deposits of sedimentary origin. A typical concentration of ^{238}U in sedimentary phosphate deposits is 1,500 Bq kg^{-1}. Uranium-238 and its decay products are generally found in close radioactive equilibrium in phosphate ore.

160. Exposures of members of the public result from effluent discharges of radionuclides of the ^{238}U decay series into the environment from phosphate rock mining and processing; from the use of phosphate fertilizers; and from the use of by-products and wastes.

1. Phosphate processing operations

161. Phosphate processing operations can be divided into the mining and milling of phosphate ore and the manufacture of phosphate products by either the wet process or the thermal process. Wet-process plants produce phosphoric acid, the starting material for ammonium phosphate and triple superphosphate fertilizers; in that process, phosphogypsum is produced as waste or by-product. Thermal process plants produce elemental phosphorus, which is in turn used primarily for the production of high-grade phosphoric acid, phosphate-based detergents and organic chemicals. Waste and by-products of the thermal process are slag and ferrophosphorus.

162. In the UNSCEAR 1988 Report [U1], the Committee estimated the collective effective dose from one year of discharge of radioactive materials into the atmosphere by phosphate industrial facilities around the world to be about 60 man Sv. Maximum annual individual effective doses were estimated to be about 40 μSv in the vicinity of an elemental phosphorus plant in the Netherlands, while equivalent doses in the lungs for individuals near six elemental phosphorus plants in the United States were calculated to range from 0.05 to 6 mSv.

163. Collective effective doses resulting from discharges into surface waters seem to be more important than those from atmospheric releases. In the Netherlands, all phosphogypsum produced by fertilizer plants (2 million tonnes per year) is discharged into the Rhine [K16]; these annual discharges, which contain about 0.4 TBq of ^{238}U, 2 TBq of ^{226}Ra, 0.7 TBq of ^{210}Pb and 2 TBq of ^{210}Po, were estimated to result in maximum annual individual effective doses of 150 μSv and in a collective effective dose of 170 man Sv per year to the Dutch population via the ingestion of seafood, ^{210}Po being the main contributor to the dose [K16]. In Spain, about 0.4 million tonnes per year of phosphogypsum produced in a phosphoric acid and fertilizer plant is discharged into the estuary of the Tinto and Odiel rivers [C17]; the annual effective dose to the critical group is estimated to be 60 μSv, the main pathway to man being the consumption of fish and crustacea [C17]. In France, over 3 million tonnes of phosphogypsum has been dumped into the Seine estuary [P1], but the corresponding radiation exposures have not been estimated.

2. Use of phosphate fertilizers

164. The concentrations of natural radionuclides in phosphate fertilizers were reviewed in the UNSCEAR 1982 Report. For a given radionuclide and type of fertilizer, the concentrations vary markedly from one country to another, depending on the origin of the components. Generally, the concentrations of ^{40}K and of ^{232}Th and its decay products are always low, and the concentrations of the radionuclides of the ^{238}U decay series are 5-50 times higher than in normal soil. Typical values are 4,000 and 1,000 Bq per kg P_2O_5 for ^{238}U and ^{226}Ra, respectively. The annual world consumption of phosphate fertilizers is about 30 million tonnes of P_2O_5. The worldwide use of phosphate fertilizers constitutes one of the most important sources of mobile ^{226}Ra in the environment [J6].

165. The amounts of fertilizer applied annually in the United States have been reported to range from about 30 kg P_2O_5 per hectare for barley, wheat and oats to about 150 kg P_2O_5 per hectare for potatoes and tobacco [N4]. The annual application of phosphate fertilizers represents less than 1% of the normal soil content of ^{238}U. Assuming an accumulation in the soil during the past 100 years, the mean additional absorbed dose in air above fertilized fields is about 1 nGy h^{-1}, a small fraction of the normal natural background from terrestrial sources of about 60 nGy h^{-1}. Small additional doses also occur from the ingestion of foodstuffs grown on fertilized agricultural land. In the UNSCEAR 1988 Report [U1], the collective effective dose resulting from the worldwide use of phosphate fertilizers during one year was roughly estimated to be 10,000 man Sv. Given the long duration of the practice at approximately the same rate, the numerical value of the annual collective dose is taken to be the same; the annual per caput effective dose would be about 2 μSv.

3. Use of by-products

166. The main by-products of phosphate industrial activities are phosphogypsum in wet-process fertilizer plants and calcium silicate slags in thermal process plants. Phosphogypsum currently has several commercial applications in the United States, including (a) as a fertilizer and conditioner for soils where peanuts and a variety of other crops are grown; (b) as a back-fill and road-base material in roadway and parking lot construction; (c) as an additive to concrete and concrete blocks; (d) in mine reclamation and (e) in the recovery of sulphur [C12]. The amount of phosphogypsum currently used for the above purposes in the United States represents about 5% of the total amount produced [C12]. In Europe and Japan, phosphogypsum has been used extensively in cement, wallboard and other building materials. Significant radiation exposures may occur if such by-products are used in the building industry.

167. Large quantities of phosphogypsum (about 100 million tonnes per year) are produced in wet-process phosphoric acid plants. The concentration of ^{226}Ra, which depends on the origin of the phosphate ore processed, is typically about 900 Bq kg^{-1}. Most of the phosphogypsum is considered waste and is either stored in ponds or stacks or discharged into the aquatic environment.

168. Phosphogypsum is used to some extent in the building industry as a substitute for natural gypsum in the manufacture of cement, wallboard and plaster. O'Riordan et al. [O1] estimated the additional doses that would be received by the occupants of a residential building in which 4.2 tonnes of by-product gypsum would have replaced the established materials. The additional absorbed dose rate in air from external irradiation was estimated to be 0.07 μGy h^{-1}, while the annual effective dose from inhalation of radon progeny was assessed at 0.6 mSv. Similar values of the annual effective dose from inhalation of radon progeny were estimated by O'Brien et al. [O2]. If it is assumed that 5% of the by-product gypsum is used as building material in dwellings, on average four persons live in each dwelling, and the mean life of a dwelling is 50 years, the collective effective doses resulting from one year of worldwide use of phosphogypsum in the building industry are estimated to be 10^5 man Sv from external irradiation and 2 10^5 man Sv from the inhalation of radon progeny. These estimates are highly uncertain and need to be confirmed by measurements in dwellings that have been constructed using known amounts of phosphogypsum.

169. The practice of using phosphogypsum in building materials is at least 50 years old [F9], but information is lacking on the amounts that have been used. If it is assumed that 5% of the current annual production (about 100 million tonnes) has been used in building materials in each of the last 50 years, it is found that 60 million houses of the current housing stock, sheltering about 5% of the world's population, have phosphogypsum included in their building materials. However, this figure seems to be too high. If it is instead assumed that 1% of the world's population lives in dwellings that include phosphogypsum in their building materials, the annual collective effective dose is estimated to be 5 10^4 man Sv. Dividing by the world's population of 5.3 10^9 yields a per caput annual effective dose of about 10 μSv.

170. Calcium silicate slag may be used as a component of concrete. Measured concentrations in slag samples range from 1,300 to 2,200 Bq kg^{-1} of ^{226}Ra [B11, M26]. Results from an indoor survey indicate that the gamma absorbed dose rate in air can

be as high as 0.3 μGy h^{-1} above background in dwellings constructed of concrete slabs containing 43% by weight slag [B11]. In a similar survey carried out in Canada, absorbed dose rates of up to 0.2 μGy h^{-1} were obtained [M26].

D. MINING AND MILLING OF MINERAL SANDS

171. Mineral sands, also called heavy minerals, are defined as those sands that have a specific gravity above 2.9. They originate from eroded inland rocks, traces of which were subsequently transported by surface waters towards the sea, where they were deposited by the combined action of wind, waves and sea currents. These mineral sands may occur under water, form part of sea, be part of the dunes or occur inland within a few tens of kilometres of the coast [K17]. Countries where mineral sands are mined include Australia, Bangladesh, Indonesia, Malaysia, Thailand and Viet-Nam.

172. Either dry mining or dredging techniques are employed in the mining of mineral sands deposits. The heavy minerals are extracted from the ore in two stages. In the first stage, a heavy mineral concentrate is extracted in a wet, gravity separation process. In a second stage, individual minerals are separated from the heavy mineral concentrate by means of dry electrostatic and magnetic techniques.

173. The heavy minerals of major commercial importance are ilmenite ($FeO \cdot TiO_2$), altered ilmenite, called leucoxene ($Fe_2O_3 \cdot TiO_2$), rutile (TiO_2), zircon ($ZrSiO_4$), monazite [a rare earth phosphate ($CePO_4$ YPO_4)] and, to a lesser extent, xenotime [a yttrium phosphate (YPO_4)]. Typical concentrations of ^{232}Th and ^{238}U in Australian heavy mineral sands, which are presented in Table 25, are much greater than the worldwide average concentrations in soils and rocks [K17].

174. Heavy minerals have numerous applications. The titaniferous minerals, once they have been processed into titanium oxide (TiO_2), are used as a pigment in paints, paper, plastics, cosmetics and ceramics. Rutile is made into titanium metal and then used, for example, in aircraft frames and jet engines. Zircon, and the associated minerals zirconia and zirconium, is used in the production of ceramics, refractory, foundry and abrasive materials, catalysts, paints, fuel cladding and structural materials in nuclear reactors. Monazite and xenotime rare earth minerals are used, for example, in the electronics, illumination and glass-making industries, in the production of magnets, superconductors and ceramics and as chemical catalysts and alloying agents in metallurgy [K17].

175. Information on exposures of members of the public resulting from the mining and milling of mineral sands is extremely scarce. In an assessment of an Australian plant, members of the public who worked on a property adjacent to the plant site were estimated to receive a dose slightly greater than 1 mSv a^{-1}, attributable mainly to external irradiation from heavy minerals spilled on the property [A9]. Away from the site, the main contribution to the dose received by members of the public results from the inhalation of dust from the plant; the highest doses were estimated to be about 0.25 mSv a^{-1} for five persons located 1.5-2 km from the plant [A9]. If the management of the plant is aware of the radiation impact of mineral sands and takes measures to control their emission, the doses will be much lower. In a study of potential radiation doses arising from a proposed mineral sand mine and processing plant in Australia, it was shown that doses to the critical group could be as low as a few μSv a^{-1} [H19].

E. SUMMARY

176. The extraction and processing of earth materials expose the general public to additional natural radiation when the earth materials, or their industrial products or by-products, contain above-average concentrations of naturally occurring radionuclides. Since very little information is available to assess those additional exposures, the related dose estimates are highly uncertain.

177. Some of those earth materials (coal, oil, peat etc.) are used to produce electrical energy by non-nuclear means. It is estimated that the production of 1 GW a of electrical energy results in collective effective doses of 20 man Sv from the use of coal, 2 man Sv from the use of peat and geothermal water or steam, 0.5 man Sv from the use of oil and 0.03 man Sv from the use of natural gas (Table 26). Taking into account the worldwide production of electrical energy in coal-fired power plants, the corresponding annual per caput effective dose is about 2 μSv. Annual per caput effective doses from other non-nuclear means of electrical energy production are much lower (Table 27).

178. Mineral sands, defined as those sands with a specific gravity greater than 2.9, usually exhibit concentrations of ^{232}Th and ^{238}U that are much greater than the worldwide average concentrations in soils and rocks. Information on exposures of members of the public resulting from the mining and milling of mineral sands is extremely scarce; annual effective doses received by critical groups may be about 1 mSv. Annual per caput effective doses have not been estimated.

179. The highest annual per caput effective doses to the public from the extractive industries are estimated to result from the use of phosphate by-products by the building industry (10 μSv), the domestic use of coal for cooking and heating (0.4-8 μSv), the use of coal ash in building materials (5 μSv) and the use of phosphate fertilizers (2 μSv). The annual per caput effective dose estimates are summarized in Table 27. The overall annual per caput effective dose arising from the extraction and processing of earth materials is estimated to be about 20 μSv.

CONCLUSIONS

180. Natural sources of ionizing radiation pervade the environment and cause exposures to all human beings. There are four main components of these exposures: cosmic rays, terrestrial gamma rays, ingested or inhaled long-lived radionuclides and inhaled radon isotopes. The first three may be said to form the basic natural radiation background because of the relative constancy of exposure. Exposures to radon and its decay products are much more widely variable. Radon gas diffuses from soils and building materials upon the decay of trace levels of radium that are naturally present. The levels of radon can build up, particularly in indoor closed spaces.

181. Doses from natural sources of radiation have been evaluated for general, worldwide geographic and geological conditions that result in normal doses and for unusual or atypical conditions that result in increased doses. The estimates of dose are for adults or for an age-weighted population if the doses to children and infants are significantly different.

182. The average annual effective doses worldwide for each of the four components of natural exposure are summarized in Table 28. For the three basic components, the annual value is 1.1 mSv. The inhalation of radon and thoron progeny results in an average annual effective dose of 1.3 mSv. The overall average annual effective dose is found to be 2.4 mSv. Small changes have been made in the various components of the effective dose; however, the compensatory effect of these changes is such that the total remains the same as in the UNSCEAR 1988 Report.

183. The importance of the inhalation of radon progeny is apparent from Table 28. It is the single most significant mechanism of human exposure to natural radiation in terms of both the average dose and the spread of doses. In middle and high latitudes, it is also the most amenable to control by building design, materials selection and ventilation. However, in low latitudes, little control can be exercised when outdoor and indoor atmospheres are not much different.

184. Radiation exposures resulting from the extraction and processing of earth materials have also been considered. These exposures are relatively small in comparison with the overall exposure from natural sources of ionizing radiation. The average annual effective dose worldwide arising from the extraction and processing of earth materials is estimated to be about 20 μSv. Because data related to those exposures are scarce, this dose estimate is highly uncertain.

Table 1
Properties of some cosmic-ray particles present in the earth's atmosphere
[E6, U5]

Class	*Name*		*Mass (MeV)*	*Mean life (s)*	*Principal mode of decay*
			Hadrons		
Nucleons	Proton	(p)	938.2	Stable	Stable
	Neutron	(n)	939.5	$1.01\ 10^{3}$	$p + e^{-} + \nu_{e}$
Mesons	Pion	($\pi^{\pm}$)	139.6	$2.55\ 10^{-8}$	$\mu + \nu_{\mu}$
		(π^{0})	134.9	$1.78\ 10^{-10}$	$\gamma + \gamma$
	Kaon	($K^{\pm}$)	493.7	$1.23\ 10^{-8}$	
		(K_1)	497.7	$0.91\ 10^{-10}$	$\mu + \nu_{\mu}$
		(K_2)	497.7	$5.7\ 10^{-8}$	$\pi + \pi$
			Leptons		
	Muon	($\mu^{\pm}$)	105.6	$2.2\ 10^{-6}$	$e^{\pm} + \nu_{e} + \nu_{\mu}$
	Electron	($e^{\pm}$)	0.511	Stable	Stable
	Neutrino	(ν_{e})	0	Stable	Stable
		(ν_{μ})	0	Stable	Stable
			Photons		
	Photon	(γ)	0	Stable	Stable

Table 2
Average annual exposures to cosmic rays

Location	*Population (millions)*	*Altitude (m)*	*Annual effective dose (μSv)*		
			Ionizing	Neutron	Total
High-altitude cities					
La Paz, Bolivia	1.0	3900	1120	900	2020
Lhasa, China	0.3	3600	970	740	1710
Quito, Ecuador	11.0	2840	690	440	1130
Mexico City, Mexico	17.3	2240	530	290	820
Nairobi, Kenya	1.2	1660	410	170	580
Denver, United States	1.6	1610	400	170	570
Tehran, Iran	7.5	1180	330	110	440
Sea level			240	30	270
World average			300	80	380

Table 3
Annual intakes by ingestion of cosmogenic radionuclides and effective doses to adults

Radionuclide	*Intake ($Bq\ a^{-1}$)*	*Annual effective dose (μSv)*
H-3	500	0.01
Be-7	1000	0.03
C-14	20000	12
Na-22	50	0.15

Table 4
Surveys of absorbed dose rates in air from terrestrial gamma radiation

Country/area	Population in 1990 (10^6)	Outdoors				Indoors				Ratio indoors to outdoors	Ref.
		Year of survey	Number of measurements	Absorbed dose rate (nGy h^{-1})		Year of survey	Number of measurements	Absorbed dose rate (nGy h^{-1})			
				Average	Range			Average	Range		
Algeria	25.0	1991	35 sites [a]	70	60-80						[B17]
Australia	16.9	1992	8 sites	93	64-123	1990	3367	103		1.11	[C11, L4]
Austria	7.6	1980	> 1000 [b]	43	20-150	1980	1900	71		1.65	[T1]
Belgium	9.9	1987	272 [c]	43	13-58	1989	300	58		1.35	[D1, S34]
Bulgaria	9.0		3670 [d]	70	48-96		1210	75	57-93	1.07	[V6]
Canada	26.5	1984	33 areas [e]	24	18-44						[G2]
Chile	13.2	1988	7 sites	60	30-90						[S3]
China	1120	1991	8805 [f]	62	2-341	1991	8805	99	11-418	1.60	[N22]
Taiwan Province	20	1989	155 sites	57	17-87						[C2]
Cuba	10.6	1990	54 sites [f]	42	26-53						[S48]
Denmark	5.1	1980	14 sites [g]	38	17-52	1987	489	63		1.66	[N6, S9, S10]
Egypt	52.4	1992	162 sites [h]	32	8-93	1991	80		14-2100		[H22, I1]
Finland	5.0	1980		65		1983		80 [k]		1.23	[L3]
France	56.1	1985	5142 [h]	68	10-250	1985	5798	75		1.10	[M3, R2]
German Dem.Rep.	16.2	1991	2000	55	<4-430	1977	158	70		1.27	[L9]
Germany, Fed.Rep. of	61.3	1978	24739 [d]	53	4-350	1978	29996	70		1.32	[B10]
Greece	10.0	1990	724 sites	42							[S4]
Hong Kong	5.9	1990	27 sites	76	37-113						[L2]
		1992	76 sites [i]	160	100-230	1992	194	190	70-290	1.17	[T12]
Hungary	10.6	1987	123 sites [j]	55	20-130	1987	123	84	10-200	1.53	[N7]
Iceland	0.25	1982		28	11-83	1982		23	14-32	0.82	[E1]
India	853	1986	2800 [i] [j]	55	20-1100						[N8]
Indonesia	184	1986		55	47-63						[S31]
Ireland	3.7	1980	284 [k]	42	<1-180	1985	223	62	10-140	1.48	[M4, M8]
Italy	57.1	1972	1365 [k]	57	7-500	1991	1500	86		1.51	[C3, C13]
Japan	123	1980	1127	49	5-100	1984	135	50 [l]		1.02	[A2, A3]
		1991	12 sites		66-144						[M23]
Luxembourg	0.4	1991	110	40							[K8]
Namibia	1.8	1991	274	120	80-260	1991	156	140	120-160	1.17	[S32]
Netherlands	15.0	1985	1049 [k]	32	10-60	1985	399	64	30-100	2.02	[J1, V1]
New Zealand	3.4					1988	716	20	<1-73		[R3]

Table 4 (continued)

Country/area	Population in 1990 (10^6)	Outdoors				Indoors				Ratio indoors to outdoors	Ref.
		Year of survey	Number of measurements	Absorbed dose rate (nGy h^{-1})		Year of survey	Number of measurements	Absorbed dose rate (nGy h^{-1})			
				Average	Range			Average	Range		
Norway	4.2	1977	234	73	20-1200	1965	2026	95		1.30	[S2, S10]
Mexico	88.6	1986/1991	1112 [j]	78	42-140						[C22]
Paraguay	4.3	1991	[l]	46	38-53						[F11]
Philippines	62.4	1991	1300	56	31-118						[D10]
Poland	38.4	1980	352 sites [l, g]	37	15-90	1984	1351		42-120		[K1, N9]
Portugal	10.3	1991	2372	85	9-226	1991	1351	105	37-244	1.24	[A7]
Romania	24.0	1979		81	32-210						[T2]
Spain	39.2	1991	1053 [k]	46	25-83	1991	100	68 [i]		1.48	[Q1, Q2]
Sudan	25.2	1991	[c, m]	53	26-690						[E5]
Sweden	8.4	1969-1989	[k]	56	41-69 [n]	1975-1978	1298	110	20-460	1.96	[M5, M9]
Switzerland	6.6	1964	3100 [g]	60							[H4]
United Kingdom	57.2	1988	25 areas [c]	34	8-89	1988	2300	60		1.76	[G3, W3]
United States	249	1972		46	13-100	1991	247	37 [i]		0.80	[M18, O3]
Population-weighted average				57				83		1.44	

[a] Ground survey with calcium sulphate thermoluminescent dosimeters and an ionization chamber.
[b] Ground survey in populated areas with a Geiger-Müller counter.
[c] Ground survey with thermoluminescent dosimeters, gamma spectrometers and ionization chambers.
[d] Ground survey with scintillation detectors.
[e] Aerial survey with a scintillation detector.
[f] Ground survey with scintillation detectors and ionization chambers.
[g] Ground survey with ionization chamber and gamma spectrometer.
[h] Ground survey with thermoluminescent dosimeters.
[i] Ground survey with energy-compensated Geiger-Müller counters.
[j] Ground survey with ionization chambers.
[k] Estimated.
[l] Calculated.
[m] 60% country coverage.
[n] Range of country averages.

Table 5
Activity concentrations of natural radionuclides in soil and absorbed dose rates in air

Radionuclide	Concentration ($Bq\ kg^{-1}$)		Dose coefficient [a]	Dose rate ($nGy\ h^{-1}$)	
	Mean [b]	Range	($nGy\ h^{-1}$ per $Bq\ kg^{-1}$)	Mean	Range
China [N22]					
K-40	580 ± 200	12-2190	0.0414	24	0.5-90
Th-232 series	49 ± 28	1.5-440	0.623	31	0.9-270
U-238 series	40 ± 34	1.8-520	-	[c]	
Ra-226 subseries	37 ± 22	2.4-430	0.461	17	1.1-200
Total				72	2-560
United States [M1]					
K-40 [U1]	370	100-700	0.0414	15	4-29
Th-232 series	35	4-130	0.623	22	2-81
U-238 series	35	4-140	-	[c]	
Ra-226 subseries	40	8-160	0.461	18	4-74
Total				55	10-200

[a] Reference [P2, S12].
[b] Area-weighted mean for China; arithmetic mean for the United States.
[c] Dose from ^{226}Ra subseries.

Table 6
Activity concentrations of natural radionuclides in various types of soil in the Nordic countries [C14]

Type of soil	Activity concentration ($Bq\ kg^{-1}$)		
	^{40}K	^{226}Ra	^{232}Th
Sand and silt	600-1200	5-25	4-30
Clay	600-1300	20-120	25-80
Moraine	900-1300	20-80	20-80
Soils containing alum shale	600-1000	100-1000	20-80

Table 7
Estimated absorbed dose rates in air within masonry dwellings

Material	Concentration ($Bq\ kg^{-1}$)			Activity utilization index [a]	Absorbed dose rate in air for indicated fractional mass of building material ($nGy\ h^{-1}$)				Reference
	C_K	C_{Ra}	C_{Th}		1.0	0.75	0.5	0.25	
Typical masonry	500	50	50	1.0	80	60	40	20	[N10]
Granite blocks	1200	90	80	1.9	140	105	70	35	[N10]
Coal ash aggregate	400	150	150	2.4	180	135	90	45	[U1]
Alum shale concrete	770	1300	67	9.0	670	500	390	170	[N10]
Phosphogypsum	60	600	20	3.9	290	220	145	70	[N10]
Natural gypsum	150	20	5	0.25	20	15	10	5	[N10]

[a] Assuming full utilization of the materials ($w_m = 1$).

Table 8
Conversion coefficients from air kerma to effective dose for terrestrial gamma rays
[P19, S12]

Radionuclides	*Conversion coefficient (Sv per Gy)*		
	Adults	*Children*	*Infants*
K-40	0.74	0.81	0.95
Th-232 series	0.72	0.81	0.92
U-238 series	0.69	0.78	0.91
Overall	0.72	0.80	0.93

Table 9
National estimates of the average annual effective dose from terrestrial gamma rays

Country	*Effective dose (mSv)*	*Reference*
Bulgaria	0.45	[V6]
Canada	0.23	[N2]
China	0.55	[N22]
Denmark	0.36	[C14]
Finland	0.49	[C14]
Germany	0.41	[B10, K9, L9]
Japan	0.32	[A6, F10]
Norway	0.48	[C14, S10]
Spain	0.40	[Q2]
Sweden	0.65	[M9, S10]
United Kingdom	0.35	[H3]
United States	0.28	[N2]
USSR	0.32	[B5]
Population-weighted world average	0.45	

Table 10
Reference annual intake of food and air
[I5, W4]

Intake	*Food consumption (kg a^{-1})*		
	Adults	*Children*	*Infants*
Milk products	105	110	120
Meat products	50	35	15
Grain products	140	90	45
Leafy vegetables	60	40	20
Roots and fruits	170	110	60
Fish products	15	10	5
Water and beverages	500	350	150
Intake	*Breathing rate (m^3 a^{-1})*		
	Adults	*Children*	*Infants*
Air	8000	5500	1400

Table 11
Reference activity concentrations of natural radionuclides in food and air

Intake	Activity concentration (mBq kg^{-1})								
	$^{238}U \rightarrow ^{234}U$	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U
Milk products	1	0.5	5	40	60	0.3	5	0.3	0.05
Meat products	2	2	15	80	60	1	10	1	0.05
Grain products	20	10	80	100	100	3	60	3	1.0
Leafy vegetables	20	20	50	30	30	15	40	15	1.0
Roots and fruits	3	0.5	30	25	30	0.5	20	0.5	0.1
Fish products	30	-	100	200	2000	-	-	-	-
Water supplies	1	0.1	0.5	10	5	0.05	0.5	0.05	0.04
Intake	Activity concentration (μBq m^{-3})								
	$^{238}U \rightarrow ^{234}U$	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U
Air	1	0.5	0.5	500	50	1	1	1	0.05

Table 12
Committed effective dose per unit activity intake of natural radionuclides for adults [14]

Radionuclide	Ingestion		Inhalation	
	Fractional transfer to blood	Dose coefficient (μSv Bq^{-1})	Class of solubility	Dose coefficient (μSv Bq^{-1})
U-238	0.05	0.025	Y	30
U-234	0.05	0.03	Y	30
Th-230	0.0002	0.07	Y	50
Ra-226	0.2	0.2	W	2
Pb-210	0.2	1	D	2
Po-210	0.1	0.2	D	1
Th-232	0.0002	0.4	Y	200
Ra-228	0.2	0.3	W	1
Th-228	0.0002	0.07	Y	100
U-235	0.05	0.03	Y	30
Pa-231	0.001	2	W	200
Ac-227	0.001	2	W	300

Table 13
Average age-weighted annual intakes of natural radionuclides and associated effective doses

Radionuclide	Ingestion		Inhalation	
	Intake (Bq)	Dose (μSv)	Intake (mBq)	Dose (μSv)
U-238	4.9	0.12	6.9	0.21
U-234	4.9	0.15	6.9	0.21
Th-230	2.5	0.18	3.5	0.18
Ra-226	19	3.8	3.5	0.01
Pb-210	32	32	3500	7.0
Po-210	55	11	350	0.35
Th-232	1.3	0.52	6.9	1.4
Ra-228	13	3.9	6.9	0.01
Th-228	1.3	0.09	6.9	0.69
U-235	0.21	0.01	0.4	0.01
Total		52		10

Table 14
Elevated values of activity concentrations of natural radionuclides in foods

Food	*Country*	*Radionuclide*	*Activity concentration in fresh food (mBq kg^{-1})*		*Ref.*
			Range	*Arithmetic mean*	
Cows' milk	Brazil	Ra-226	29-210	108	[A4]
		Pb-210	5-60	45	[A8]
Chicken meat	Brazil	Ra-226	37-163	86	[L10]
		Ra-228	141-355	262	
Beef	Brazil	Ra-226	30-59	44	[L10]
		Ra-228	78-111	96	
Pork	Brazil	Ra-226	7-22	13	[L10]
		Ra-228	93-137	121	
Reindeer meat	Sweden	Pb-210	400-700	550	[P7]
		Po-210	-	11000	
Cereals	India	Ra-226	up to 510	174	[L6]
		Th-228	up to 5590	536	
Corn	Brazil	Ra-226	70-229	118	[V3]
		Pb-210	100-222	144	
Rice	China	Ra-226		250	[Z1]
		Pb-210		570	
Green vegetables	India	Ra-226	325-2120	1110	[L6]
		Th-228	348-5180	1670	
Carrots	Brazil	Ra-226	329-485	411	[V3]
		Pb-210	218-318	255	
Roots and tubers	India	Ra-226	477-4780	1490	[L6]
		Th-228	70-32400	21700	
Fruits	India	Ra-226	137-688	296	[L6]
		Th-228	59-21900	2590	

Table 15
Elevated values of activity concentrations of natural radionuclides in potable waters of various sources

Source	*Country*	*Radionuclide*	*Activity concentration (mBq l^{-1})*			*Reference*
			Range	*Arithmetic mean*	*Geometric mean*	
Bottled waters	Brazil	Ra-226	<10-130		27	[P8]
		Pb-210	<50-190		77	
	France	U-238	up to 2000	60		[P5, P9, S11]
		Ra-226	up to 2700	60		[R12, R13, R14,
		Th-232	-	< 40		M19]
	Germany	U-238	<1-140		4.4	[B12,
		Ra-226	<1-1800		25	G4, G5]
		Pb-210	3.3-53		9.0	
		Po-210	0.4-8.9		1.8	
	Indonesia	Ra-226	<1-60	22	-	[S31]
	Portugal	Ra-226	<3-2185		26.7	[B6]
		Pb-210	2-392		18.5	
Ground waters	Finland	U-238	up to 74000	4200		[S15]
		Ra-226	up to 5300	440		
		Pb-210	up to 10200	430		
		Po-210	up to 6300	220		
	Sweden	Ra-226	2-2460	45	13.7	[K4]
	Yugoslavia	Ra-226	0.5-510	60	-	[K11]

Table 16
Alpha decay properties of ^{220}Rn and ^{222}Rn with short-lived decay products
[B7, M11]

^{220}Rn					^{222}Rn			
Radionuclide	*Branch (%)*	*Half-life*	*Energy (MeV)*	*Intensity (%)*	*Radionuclide*	*Half-life*	*Energy (MeV)*	*Intensity (%)*
Rn-220		55 s	6.29	100	Rn-222	3.824 d	5.49	100
Po-216		0.15 s	6.78	100	Po-218	3.04 min	6.00	100
Pb-212		10.64 h	β, γ	-	Pb-214	26.8 min	β, γ	-
Bi-212		60.6 min	6.05	25	Bi-214	19.7 min	β, γ	-
			6.09	10	Po-214	163.7 μs	7.69	100
Po-212	64	304 ns	8.78	100				
Tl-208	36	3.10 min	β, γ	-				

Table 17
Activity concentrations of ^{226}Ra and ^{228}Ra in various types of rock
[W6]

Type of rock	*Example*	*Concentration (Bq kg^{-1})*			
		^{226}Ra		^{228}Ra	
		Arithmetic mean	*Range*	*Arithmetic mean*	*Range*
Acid intrusive	Granite	78	1-370	111	0.4-1030
Basic extrusive	Basalt	11	0.4-41	10	0.2-36
Chemical sedimentary	Limestone	45	0.4-340	60	0.1-540
Detrital sedimentary	Clay, shale, sandstone	60	1-990	50	0.8-1470
Metamorphosed igneous	Gneiss	50	1-1800	60	0.4-420
Metamorphosed sedimentary	Schist	37	1-660	49	0.4-370

Table 18
Activity concentrations of natural radionuclides in various types of rock in the Nordic countries
[C14]

Rock type	*Activity concentration (Bq kg^{-1})*		
	^{40}K	^{226}Ra	^{232}Th
Normal granite	600-1800	20-120	20-80
Thorium- and uranium-rich granite	1200-1800	100-500	40-350
Gneiss	600-1800	20-120	20-80
Diorite	300-1000	1-20	4-40
Sandstone	300-1500	5-60	4-40
Limestone	30-150	5-20	1-10
Shale	600-1800	10-120	8-60
Middle Cambrian alum shale	1000-1800	120-600	8-40
Upper Cambrian or Lower Ordovician alum shale	1000-1800	600-4500	8-40

Table 19
Parameters of emanation and diffusion of ^{222}Rn from the earth and from building materials

Material	*Representative value*	*Range*	*Ref.*
Emanation fraction			
Rock (sieved)	0.084 [a]	0.005 - 0.40	[B8]
Soil (various)	0.23 [a]	0.02 - 0.83	[D5]
Brick (clay)	0.04 [b]	0.02 - 0.1	[S17]
Concrete (ordinary)	0.15 [c]	0.1 - 0.4	[S17]
Gypsum (natural)	0.08 [b]	0.03 -0.2	[S17]
Porosity			
Earth	0.25	0.01-0.5	[F6, H14,
Building materials	0.15	0.01-0.7	O5, S19]
Diffusion coefficient ($m^2 s^{-1}$)			
Earth	$5\ 10^{-7}$	10^{-11}-10^{-6}	[F6, H14,
Building materials	$1\ 10^{-8}$	10^{-11}-10^{-6}	O5, S19]

[a] Arithmetic mean.
[b] Inferred from range.
[c] Inferred from range and mix.

Table 20
Flux density from the convection of radon and the resultant entry rates into the model building caused by an underpressure of 5 Pa with varying permeability of the subjacent earth

Circumstance	*Flux density ($Bq\ m^{-2}\ s^{-1}$)*					*Entry rate ($Bq\ m^{-3}\ h^{-1}$)*				
	Permeability (m^2)					*Permeability (m^2)*				
	10^{-13}	10^{-12}	10^{-11}	10^{-10}	10^{-9}	10^{-13}	10^{-12}	10^{-11}	10^{-10}	10^{-9}
Cracked floor [a]	0.0071	0.0078	0.014	0.078	0.043	10	11	20	112	62
Bare earth	0.028	0.030	0.043	0.19	0.085 [b]	40	43	62	274	122 [b]

[a] With an array of 1 cm cracks every 1 m of floor. Values averaged over whole floor.
[b] Trend adjustment of published data [W8].

Table 21
Average radon concentrations and percentage utilization of water supplies
[N18, O5]

Type of supply	*Concentration (Bq m^{-3})*			*Utilization (%)*		
	United States	*United Kingdom*	*Reference value*	*United States*	*United Kingdom*	*Reference value*
Surface water	1100	1000	1000	50	66	60
Ground water	11500	30000	10000	32	34	30
Well water	208000	< 1000000	100000	18	< 1	10

Table 22
Illustrative radon entry rates for the model masonry building in a temperate climate

Source of radon	*Mechanism*	*Entry rate (Bq m^{-3} h^{-1})*	*Percentage*
Building elements	Diffusion	10	21
Subjacent earth	Diffusion	7.5	15
	Advection	20	41
Outdoor air	Infiltration	10	20
Water supply	De-emanation	1	2
Natural gas	Consumption	0.3	1
All sources and mechanisms		49	100

Table 23
Radon concentrations in dwellings determined in indoor surveys

Country/area	*Year of survey*	*Type of survey*	*Duration of exposure*	*Number of dwellings surveyed*	*Radon concentration (Bq m^{-3})*			*Geometric standard deviation*	*Ref.*
					Arithmetic mean	*Geometric mean*	*Maximum value*		
Algeria	1987	Exploratory	60 days	50	32		137		[C9]
Argentina, 3 cities	1990	Preliminary		180	32	31	127	2.0	[G6]
Australia	1990	National	1 year	3413	12	8.7	423	2.1	[L4]
Austria, Salzburg	1980	Local	Grab samples	729	-	15	190	-	[S40, S41]
Belgium	1991	National	6 months	450	48		4000		[V8]
Canada	1977-1980	National	Grab samples	13413	34	14	1724	3.6	[L7]
Canada, Nova Scotia	1990	Regional	3 months	719	108	-	5920	3.6	[J9]
China, seven provinces	1989	Regional		3945	24	20	378	2.2	[Z2]
China, Sechuan	1990	Regional		1967	19	17	170	1.7	[C10]
China, Shenzhen	1986	Regional		69	16	14	54	2.0	[R5]
Czechoslovakia	1982	National	Grab samples	1200	140 [a]	-	20000	-	[T6, T8]
Denmark	1985	National	6 months	496	47	29	560	2.2	[S9, U15]
Egypt	1991	National		329	9.0		24		[K12]
Finland	1982	National	1 month	8150	90	64	-	3.1	[C19, C21]
France	1988	National	60 days	3006	62	41	4687	2.7	[R6, R7]
Germany (former Fed. Republic)	1984	Regional	3 months	5970	49	40	-	1.8	[S29]
Germany, Cottbus	1989	Regional	3 months	67	35	23	153	2.5	[L9]
Germany, Saxony and Thuringia	1990	Exploratory	3 days	5000	270	190	115000	2.4	[L9]
Germany (former Fed. Republic)	1991	Regional	3 days	1040	57	34	3100	2.9	[K13]
Ghana, Legon	1990	Exploratory	9 months	25			340		[O6]
Greece	1988	Exploratory	6 months	73	52		492		[G7]
Hong Kong	1991	Regional		140	41		140		[T9]
India	1991	Exploratory	3 months	1208	57	42	214	2.2	[S37]
Indonesia	1991	Exploratory		165	12		120		[S31]
Iran, 4 cities	1988	Exploratory	90 days	121	82		3070		[S26]
Ireland	1987	National	6 months	736	-	37	1700	-	[C18]
Italy	1991	National	1 year	2250	80	62		1.9	[B15, B16]
Japan	1990	National	1 year	6000	29	23		1.6	[K5]
Kuwait	1988	Exploratory	1 year	69	41		103		[M13]
Luxembourg	1991	National		2500		65			[K8]
Netherlands	1982-1984	National	1 year	1000	29	24	118	1.6	[H17,P24,P25]
New Zealand	1988	National	1 year	717	20	18	94		[R3]
Norway	1991	National	6 months	7500	60	30			[S39]
Pakistan	1991	Exploratory	2.5 months	50	30		83		[T10]
Poland	1991	Preliminary	1 year	345	38		568		[B14]
Portugal	1991	National	4 months	4200	81	37	2795		[F14]
Spain	1991	National		1700	86	43	15400	3.7	[Q2, Q3]
Sweden	1980-1982	National	2 weeks	512	108	62	3310		[M17, S42]
Sweden	1990-1991	National	3 months	1360	108	56	3900		[S43]
Switzerland	1991	National	2.5 months	1600	70		3000		[S38]
Syria, 2 areas	1990	Exploratory	6 months	77	20		72		[O7]
United Kingdom	1991		3 months	96000	20		10000		[W9]
United States	1991	National	1 year	5967	46	25		3.1	[M24, U12]
United States, New York	1988	Regional	1 year	2043	42	26	1420	2.7	[P11]
Median values					42	30		2.2	

[a] Derived from radon EEC measurements, using an equilibrium factor of 0.4.

Table 24
Average concentrations in air of radon and thoron, including their decay products, and annual effective doses

Radionuclide	*Location*	*Concentration* ($Bq\ m^{-3}$)		*Effective dose coefficient* ($nSv\ per\ Bq\ h\ m^{-3}$)		*Annual effective dose* [a] (μSv)	
		Gas	*EEC* [b]	*Gas*	*EEC*	*Gas*	*EEC*
Radon	Outdoors	10	8	0.17	9	3.0	130
	Indoors	40	16	0.17	9	48	1000
Total (rounded)						1200	
Thoron	Outdoors	10	0.1	0.11	10	1.9	1.8
	Indoors	3	0.3	0.11	32	2.3	67
Total (rounded)						73	

[a] Weighted for occupancy: 0.2 outdoors, 0.8 indoors.
[b] The equilibrium equivalent concentration (EEC) of radon (or thoron) is the product of the concentration of radon (or thoron) and of the equilibrium factor between radon (or thoron) and its decay products. The values of the equilibrium factor have been taken to be 0.8 outdoors and 0.4 indoors for radon. Thoron EEC values are based on measurements.

Table 25
Typical concentrations of ^{232}Th and ^{238}U in heavy mineral sands in Australia
[K17]

Mineral	^{232}Th *concentration* ($Bq\ kg^{-1}$)	^{238}U *concentration* ($Bq\ kg^{-1}$)
Ore	60-200	40
Heavy mineral concentrate	1000-1300	<100
Ilmenite	600-6000	<100-400
Leucoxene	1000-9000	250-600
Rutile	<600-4000	<100-250
Zircon	2000-3000	200-400
Monazite	600000-900000	10000-40000
Xenotime	180000	50000
Average soil and rock	40	40

Table 26
Estimates of collective effective dose per unit electrical energy generated by non-nuclear sources

Source	*Normalized collective effective dose* [man Sv $(GW\ a)^{-1}$]
Coal	20
Oil	0.5
Natural gas	0.03
Geothermal	2
Peat	2

Table 27
Estimates of annual per caput effective doses resulting from the extraction and processing of earth materials

Source	*Annual per caput effective dose (μSv)*
Coal	
Mining	0.0001-0.002
Electrical energy production	2
Domestic use	0.4-8
Use of fuel ash	5
Other non-nuclear sources of electrical energy production	
Oil	0.01
Natural gas	0.001
Geothermal	0.001
Exploitation of phosphate rock	
Industrial operations	0.04
Fertilizers	2
By-products and wastes	10

Table 28
Average annual effective dose to adults from natural sources of ionizing radiation

Component of exposure	*Annual effective dose (mSv)*	
	In areas of normal background	*In areas of elevated exposures*
Cosmic rays	0.38	2.0
Cosmogenic radionuclides	0.01	0.01
Terrestrial radiation: external exposure	0.46	4.3
Terrestrial radiation: internal exposure (excluding radon)	0.23	0.6
Terrestrial radiation: internal exposure from radon and its decay products		
Inhalation of Rn-222	1.2	. 10
Inhalation of Rn-220	0.07	0.1
Ingestion of Rn-222	0.005	0.1
Total	2.4	-

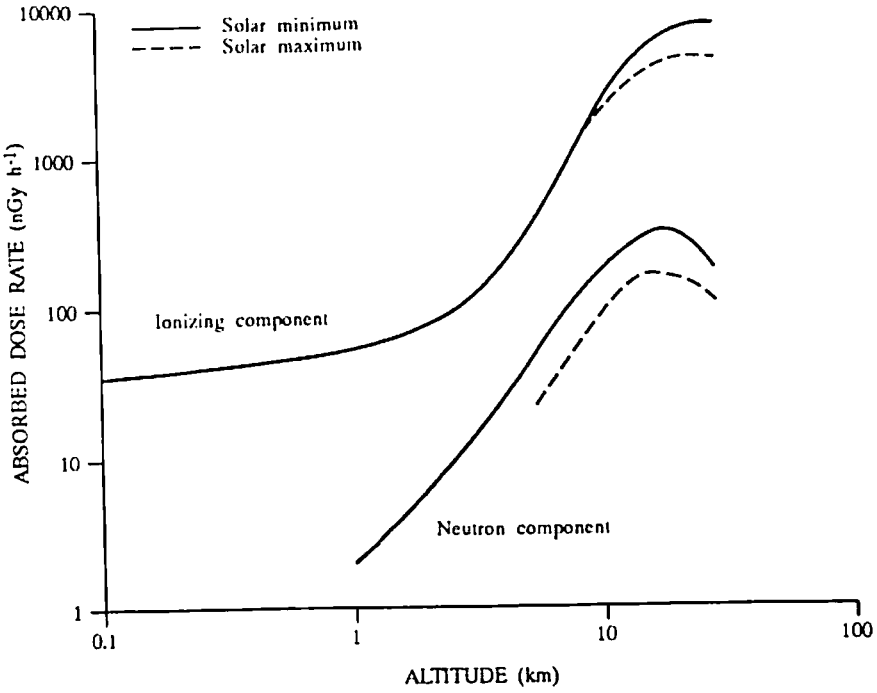

Figure 1.
Absorbed dose rate in air at 50° geomagnetic latitude from the ionizing and neutron components of cosmic rays as a function of altitude.
[U3]

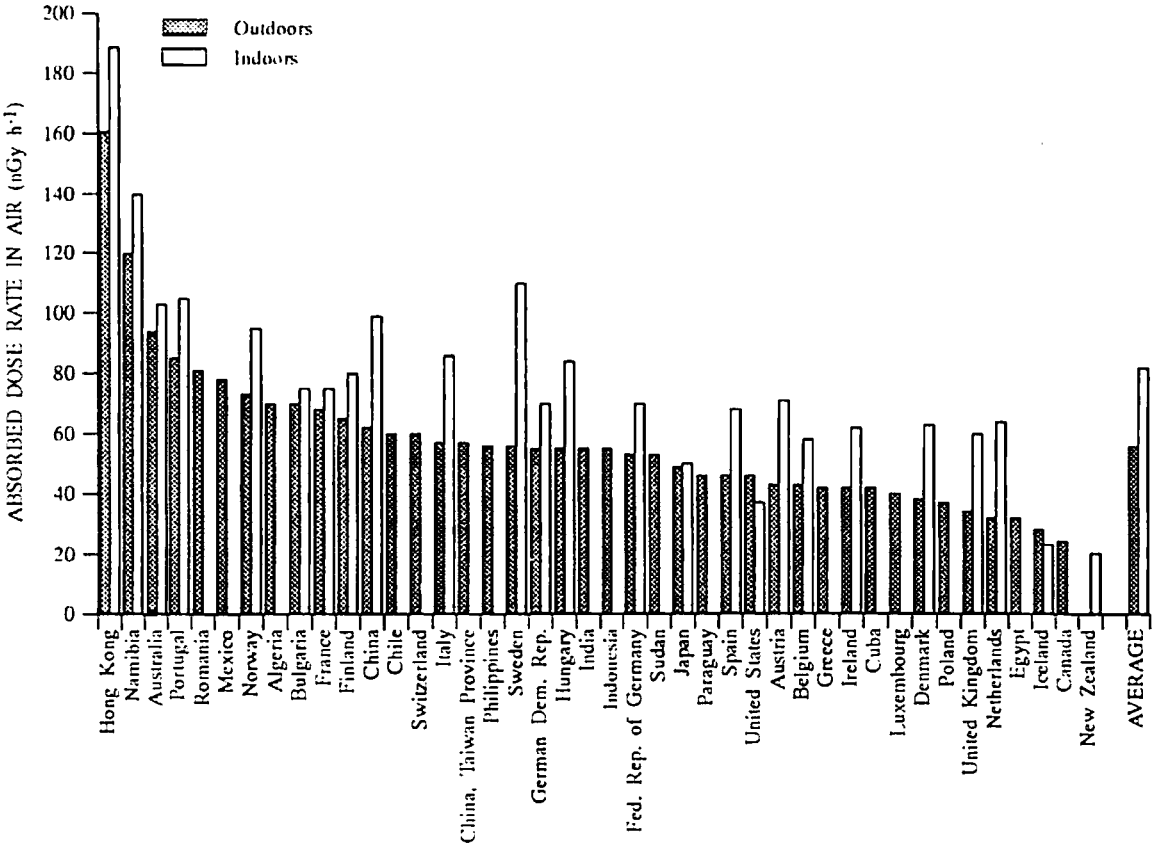

Figure II.
Absorbed dose rates in air from terrestrial gamma radiation ranked according to levels outdoors.

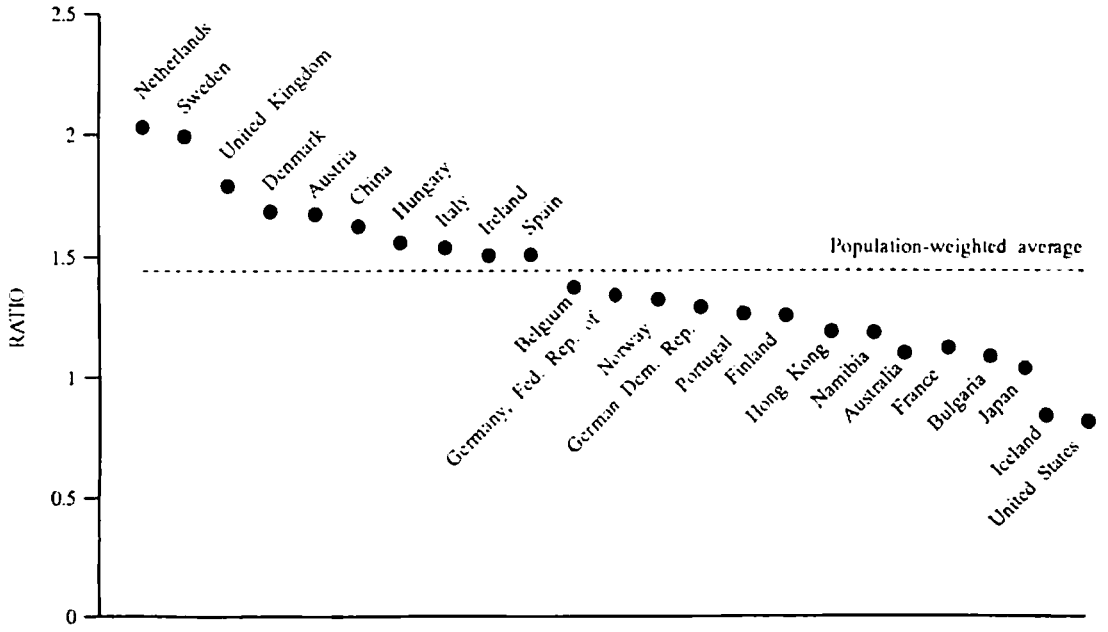

Figure III.
Ratio of indoor to outdoor absorbed dose rates in air from terrestrial radiation.

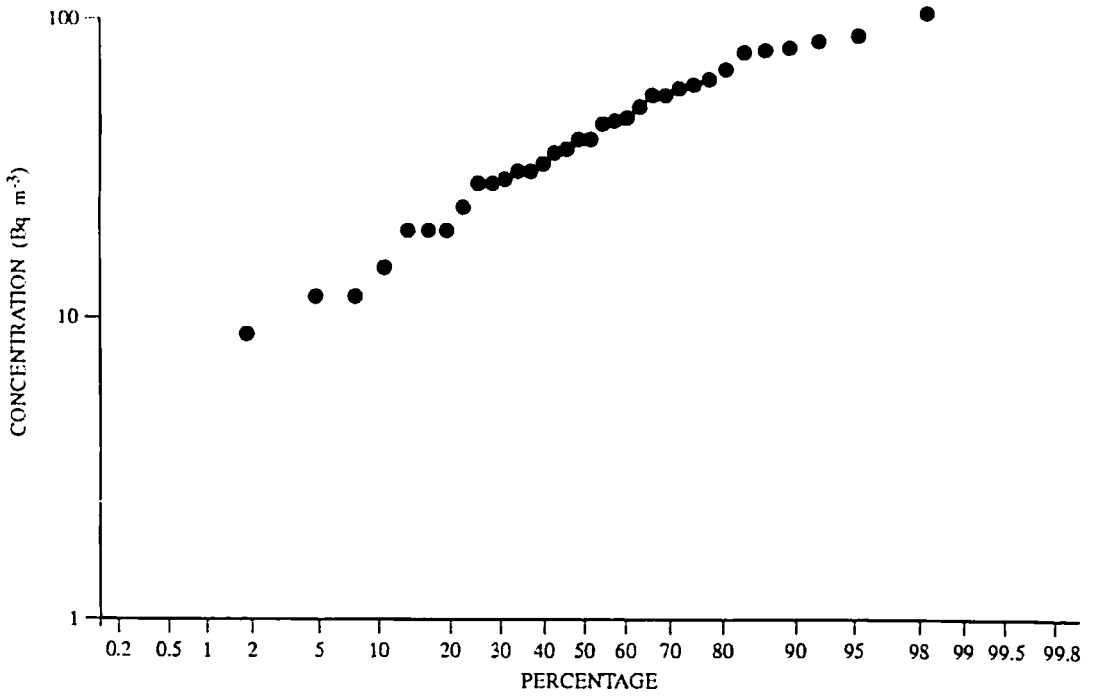

Figure IV.
Distribution of survey measurements of radon concentrations indoors.

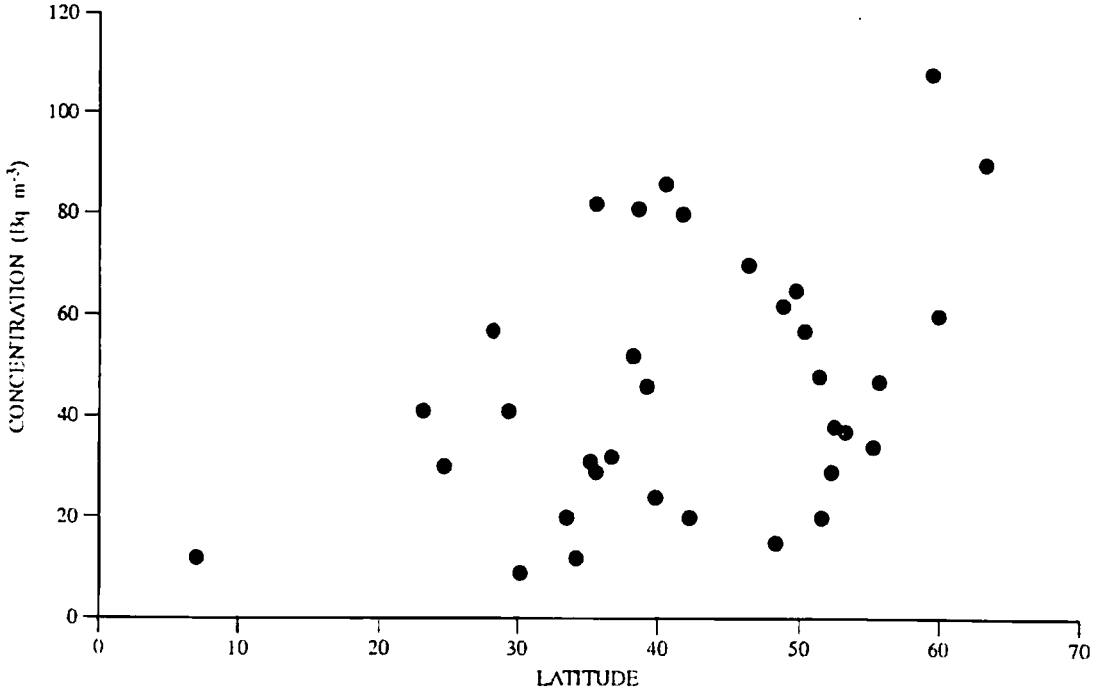

Figure V.
Radon concentrations indoors in relation to latitude.
The population-weighted average is 40 Bq m^{-3}.

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