IONIZING RADIATION: SOURCES AND BIOLOGICAL EFFECTS

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on the Effects of Atomic Radiation

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NOTE

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ANNEX B

Exposures to natural radiation sources

CONTENTS

Introduction

1. The assessment of the radiation doses from natural sources in humans is of particular importance because natural radiation is the largest contributor to the collective dose of the world population. The natural radiation sources are classified into:

(a) External sources of extraterrestrial origin (cosmic rays) and of terrestrial origin, i.e., the radioactive nuclides present in the crust of the earth, in building materials and in the air;

(b) Internal sources, comprising the naturally-occurring radionuclides which are taken into the human body.

This Annex is to a large extent a summary of Annex B of the 1977 report of the Committee [U1]. Modifications have been made only for those components of the natural radiation environment for which knowledge has substantially improved since 1977. The doses due to the radon isotopes and to their short-lived decay products are briefly reviewed; a detailed treatment of the sources of exposure to those radionuclides and of the corresponding doses is provided in Annex D.

I. EXTERNAL IRRADIATION

A. COSMIC RAYS

2. The high-energy radiation that enters the earth's atmosphere from outer space is known as primary cosmic rays. When these interact with atomic nuclei in the atmosphere, secondary particles and electromagnetic radiation are produced which are called secondary cosmic rays.

1. Primary cosmic rays

3. Most of the primary cosmic rays originate outside of the solar system. In addition, there are also solar cosmic rays related to solar flares.

(a) Primary galactic cosmic rays

4. Primary galactic cosmic rays consist largely of high-energy protons which enter the solar system from

interstellar space, together with ^{4}He ions in the proportion of about 10% and much smaller proportions of heavier particles, and of electrons, photons and neutrinos. The primary flux density is affected by the earth's magnetic field, which deflects low-energy charged particles back into space. This effect is dependent on the geomagnetic latitude, so that the flux density of low-energy protons at the top of the atmosphere is greater at the poles than in equatorial regions. Thus, as shown in Figure I, the ion density production rate at a given altitude in the atmosphere (which is a function of the "atmospheric depth" i.e., of the mass of air above a unit of area at that altitude) is latitude dependent.

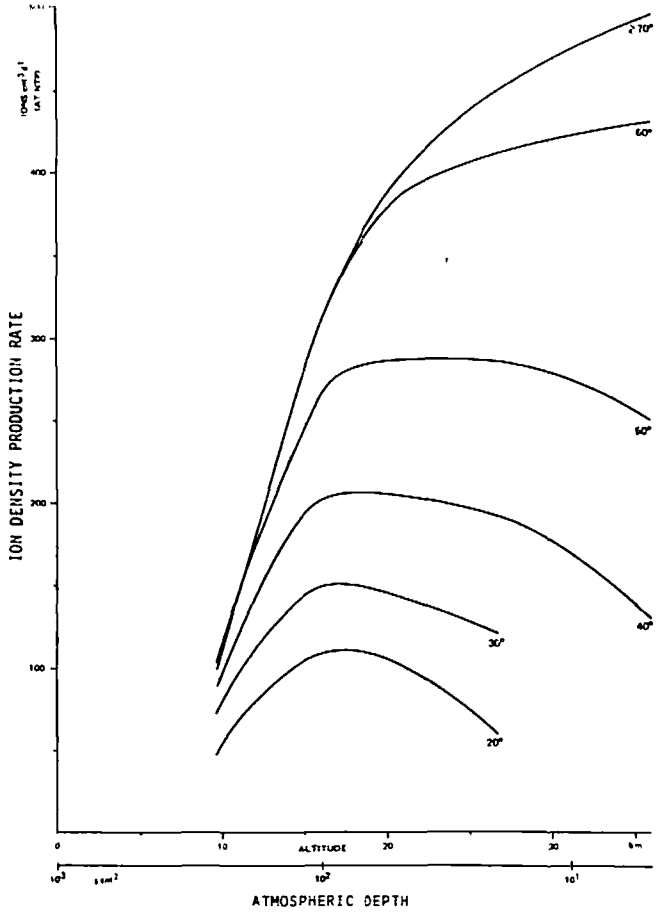

Figure I. Variation of ion density production rate with altitude and atmospheric depth at different geomagnetic latitudes. Based upon the results of Neher [N1]

5. The fluence rate of the galactic low-energy protons in the upper atmosphere varies with time according to the 11-year solar cycle. This is known as modulation. The fluence rate is at a minimum during times of maximum solar activity and passes through a maximum during the period of low solar activity.

(b) Primary solar cosmic rays

6. During the solar flares, large numbers of charged particles, mainly protons and alpha particles, are released. However, these particles have relatively low energies and do not usually cause significant increases in radiation doses at the earth's surface.

2. Secondary cosmic rays

7. When primary cosmic-ray particles enter the atmosphere, those with higher energy undergo nuclear reactions (spallation reactions) with nuclei of atoms present in the air, producing neutrons, protons, pions, and kaons, and quite a variety of reaction products (cosmogenic nuclides) such as ^{3}H, ^{7}Be, ^{10}Be, ^{22}Na, and ^{24}Na. The high-energy protons, neutrons and pions thus formed react further with nuclei in the air to form more secondary particles [G1, P1]. Such a process is called a cascade. The pions decay into muons or photons, initiating other cascades.

8. The protons and neutrons contribute significantly to the absorbed dose index rate[1] in the upper atmosphere. The neutrons lose energy by elastic collisions, and when thermalized they are captured by ^{14}N to form ^{14}C. Because nucleons rapidly lose energy by ionization and nuclear collisions, the nucleonic fluence rate is considerably attenuated in the lower part of the atmosphere and accounts for only a few per cent of the absorbed dose index rate from cosmic rays at sea level. The major contribution here is provided by the muons produced by the decay of charged pions at higher altitude and by the electrons that result from ionization, from muon decay and from cascade processes.

[1] The absorbed dose index rate is the maximum absorbed dose rate that would occur in a 30-cm diameter tissue equivalent sphere located with its centre at the point of interest.

3. Absorbed dose indexes from cosmic rays

9. The doses from directly ionizing components of cosmic rays and from neutrons will be examined separately.

(a) Ionizing component

10. The ion production rate per unit volume in free air is a measure of the fluence rate of the total charged-particle component of the cosmic-ray field and is usually expressed as the number of ions formed per second in each cubic centimetre of air at normal temperature and pressure (STP). The values of the cosmic ray ion density production rate at sea level reported after 1960 show a 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} [G2, G3, H1, K1, L1, O1, O2, S1, Y1]. Here, as in Annex B of the 1977 report [U1], a value of 2.1 cm^{-3} s^{-1} will be used for the purposes of computing the absorbed dose index rate. Assuming each ion pair in moist air requires 33.7 eV to be produced, the absorbed dose rate in air is 3.2 10^{-8} Gy h^{-1}. This value is taken to be numerically equal to the absorbed dose index rate. About 75% of the dose is from muon collision electrons, 15% from muon decay electrons, and 10% from other processes [N2]. If the shielding effect by building structures is not taken into account, the annual absorbed dose index is found to be 2.8 10^{-4} Gy at ground level. Using reported values of ion density production rate in the upper atmosphere, absorbed dose index rates have been computed there in a similar manner and are shown in Figure II [U1].

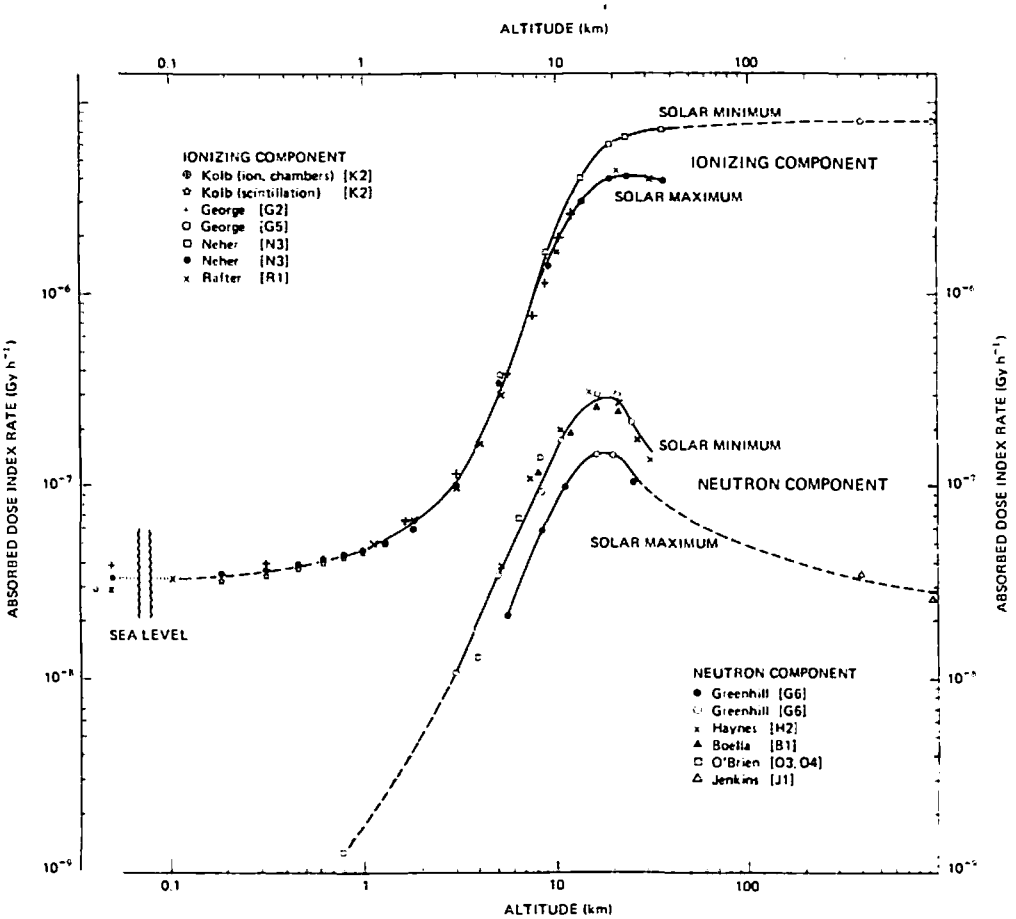

Figure II. Absorbed dose index rates at high geomagnetic latitudes (50°) from the ionizing and neutron components of cosmic rays at different altitudes for 1969 (solar maximum) and 1965 (solar minimum). The ionizing component of the absorbed dose index rate at 0.1 km is inferred from that at ground level

(b) Neutron component

11. As in Annex B of the 1977 report of UNSCEAR, a neutron fluence rate of 8 10^{-3} cm^{-2} s^{-1} at sea level is adopted for the purpose of estimating doses at high latitudes. Using a conversion factor from neutron fluence rate to absorbed dose index rate of 5 10^{-8} Gy h^{-1} cm^2 s [H3], the absorbed dose index rate would be 4 10^{-10} Gy h^{-1}, yielding an annual absorbed dose index of 3.5 10^{-6} Gy at ground level. The neutron absorbed dose index rate increases rapidly with altitude, reaching a maximum at altitudes between 10 and 20 km (Figure II).

4. Annual effective dose equivalents from cosmic rays

12. For both the ionizing and the neutron component, the absorbed dose index is assumed to represent sufficiently well the absorbed dose in all organs and tissues of the body. Using a value of one for the quality factor of the ionizing radiation, the annual effective dose equivalent is thus found to be 280 μSv at ground level.

13. For the neutron component a quality factor of 6 is adopted, as in Annex B of the 1977 report of the Committee [U1], on the basis of computations of the dose equivalent and of the absorbed dose by Hajnal et

al. [H3] for isotropic bilateral incidence on a slab averaged to a depth of 15 cm. The annual effective dose equivalent for the neutron component is thus estimated to be 21 μSv at ground level.

B. EXTERNAL RADIATION FROM NATURALLY-OCCURRING RADIONUCLIDES (TERRESTRIAL RADIATION)

1. Source radionuclides

14. The natural radionuclides in the environment are of two general classes, the cosmogenic and the primordial. The cosmogenic radionuclides (^{3}H, ^{7}Be, ^{14}C, ^{22}Na, ^{24}Na, etc.), which are mainly produced through interaction of the cosmic rays with target atoms in the atmosphere, do not contribute significantly to the external gamma radiation doses at ground level.

15. The main primordial radionuclides are ^{40}K, ^{87}Rb, and the elements of the two radioactive series headed by ^{238}U and ^{232}Th, which are presented in Figures III and IV and have existed in the earth's crust throughout its history. Other radionuclides, such as those present in the ^{235}U decay series, have been neglected as they contribute very little to the total dose from natural background.

16. It should be mentioned that ^{238}U is not only the head of a radioactive decay series but also gives rise to many radioactive nuclides by spontaneous fission. The inventory of the long-lived fission products in the earth's crust is rather large, but the average activity concentrations in soil are extremely small and the resulting doses trivial. Taking ^{90}Sr as an example, the inventory in the earth's crust is estimated to be $5\ 10^{16}$ Bq [S2]; its activity concentration in soil would be $2\ 10^{-6}$ Bq kg^{-1}, yielding an annual dose in red bone marrow of the order of 10^{-11} Gy.

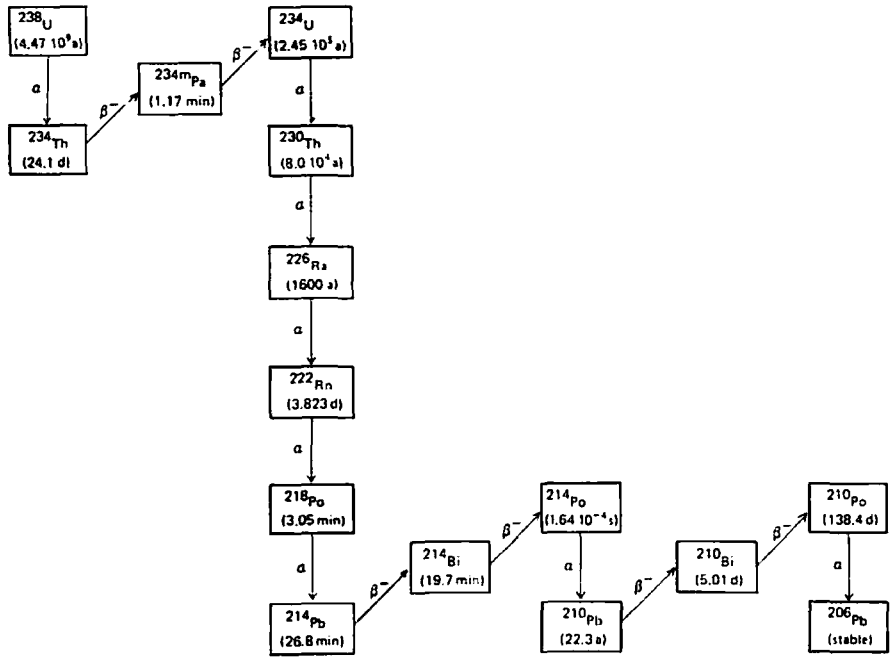

Figure III. Uranium-238 decay series. Radionuclides produced in less than one per cent of the transformations of the parent nuclide are not shown [L8]

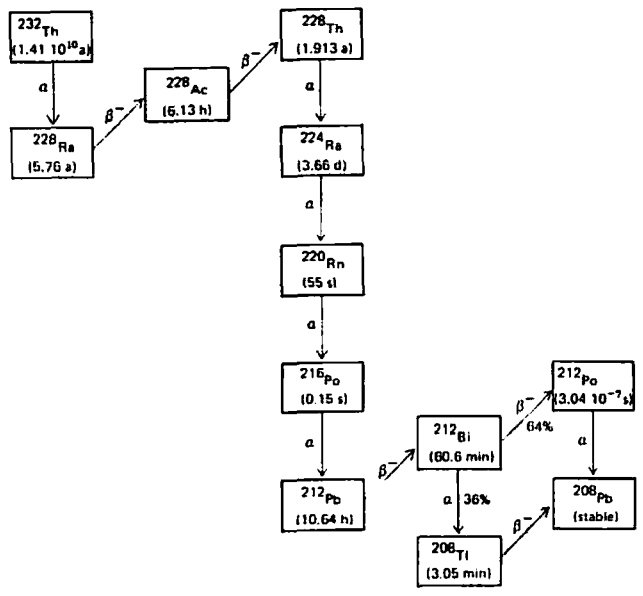

Figure IV. Thorium-232 decay series [L8]

2. Exposure outdoors

17. The concentration of radionuclides in soil, which is directly relevant to the outdoor exposure, is largely determined by the activity concentration in the source rock. Igneous rocks generally exhibit higher activity concentrations than sedimentary rocks, while metamorphic rocks have concentrations typical of the rocks from which they were derived. However, certain sedimentary rocks, notably some shales and phosphate rocks, are highly active [N2]. The average activity concentrations of ^{40}K, ^{238}U and ^{232}Th in soil and the corresponding absorbed dose rates in air 1 m above the ground surface, calculated on the assumption that all decay products of ^{238}U and ^{232}Th are in radioactive equilibrium with their precursors, are given in Table 1. The average outdoor terrestrial absorbed dose rate in air from gamma radiation would be 4.4 10^{-8} Gy h^{-1}, and the relative contributions of ^{40}K, ^{238}U and ^{232}Th about 35%, 25% and 40%, respectively.

18. Several surveys have been performed over whole countries and areas for the purpose of estimating the exposure of the relevant populations to outdoor external gamma radiation. Since the publication of the 1977 report of the Committee [U1], results have been reported from Denmark, France, Ireland, Japan, Norway, Poland and Romania: they are summarized in Table 2.

19. Intercomparisons between the above surveys are difficult as they were conducted using different methods and types of instrumentation. The results are also not altogether coherent as regards the quantity measured. Often in the same survey significant differences were shown when several types of instrumentation were used [N6]. Despite these difficulties, country-averaged absorbed dose rates in air fall within the relatively narrow range of 3.7 to 9.4 10^{-8} Gy h^{-1}, with a population-weighted average of 4.9 10^{-8} Gy h^{-1}. The population involved represents about 30% of that of the world, while the corresponding area covered is about 10% of the total land surface. The population-weighted value of 4.9 10^{-8} Gy h^{-1} is in relatively good agreement with the estimate of 4.5 10^{-8} Gy h^{-1} derived by the Committee in Annex B of the 1977 report [U1] for the global average of the absorbed dose rate in air, 1 m above ground, from gamma terrestrial radiation. A rounded value of 5 10^{-8} Gy h^{-1} will be adopted in this Annex.

20. The variability of the exposure around the mean values can be roughly assessed from the detailed results relative to the administrative subdivisions of France, the Federal Republic of Germany, Italy, Japan and the United States. Figure V presents the population-weighted frequency distribution of the outdoor absorbed dose rate in air from terrestrial radiation obtained from the combined data of the five countries.

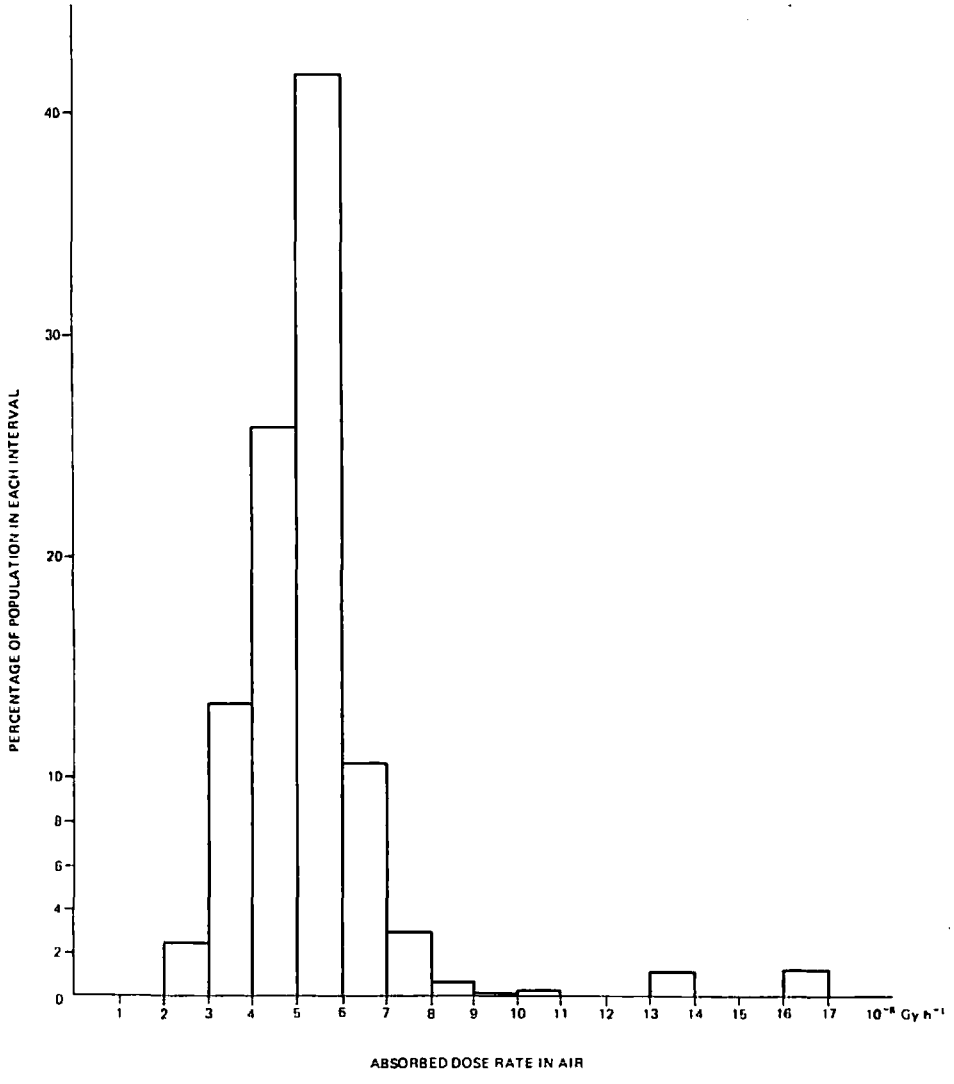

Figure V. Frequency distribution of outdoor absorbed dose rate in air from terrestrial radiation. Combined data from France [M8], the Federal Republic of Germany [C8], Italy [C2], Japan [A3] and the United States [O7]

From Figure V, it is seen that a large fraction of the population lives in areas where the population-weighted distribution of the outdoor absorbed dose rate in air is normally distributed, while another fraction, much smaller, lives in areas outside of the normal distribution. The average absorbed dose rate in air in the "normal" areas of the five countries is 5.2 10^{-8} Gy h^{-1}, with a standard deviation of approximately 1 10^{-8} Gy h^{-1}. Assuming that the distribution holds on a global basis, 95% of the world population residing in areas of "normal" natural radiation would live where the outdoor absorbed dose rate in air from the primordial radionuclides falls between about 3 and 7 10^{-8} Gy h^{-1}. However, it should be borne in mind that these values are themselves averages, corresponding to population groups of at least 10^5 people.

21. As shown in Figure V, there are regions in the world where the outdoor terrestrial radiation substantially exceeds the normal range of variation. In addition to the Italian provinces of Lazio and Campania, such regions are known to exist in Brazil, France, India, Iran, Madagascar and Nigeria [B3]. The best known from a dosimetric point of view are those located in Brazil and India.

22. Deposits of radioactive minerals rich in monazite occur in littoral formations along the coastal regions of India. Of particular interest is a stretch about 250 km long and about 0.5 km wide on the south-west coast in the states of Kerala and Tamil Nadu. The most concentrated deposits along the Kerala coast are located on a 55 km strip populated by about 70 000 persons, where the thorium concentration in the monazite ranges from 8.0 to 10.5% by weight, being the highest known in the world [G7]. Gopal-Ayengar et al. [G7, G8] carried out a dosimetric survey using thermo-luminescent dosimeters distributed to 8513 individuals of the population of that 55 km strip. Assuming an homogeneous whole-body irradiation, the average absorbed dose rate for the 70 000 people residing in the region can be estimated at 4.3 10^{-7} Gy h^{-1}; about 24% of the people would experience average absorbed dose rates in excess of 5.7 10^{-7} Gy h^{-1}, about 6% would exceed 10^{-6} Gy h^{-1} and about 0.7% would exceed 2.3 10^{-6} Gy h^{-1}. As the thermoluminescent dosimeters were worn on a 24-hour basis, these results represent an average (outdoors plus indoors) absorbed dose rate from terrestrial radiation.

23. Two types of high-background regions have been found in Brazil: the monazite sand region along the Atlantic coast of the states of Espirito Santo and Rio de Janeiro and the volcanic intrusive anomalies along a geological fracture that extends from the coast through the inland state of Minas Gerais [P2].

24. Along the Atlantic coast, the radiation levels in three towns (Guarapari, Meaipe and Cumuruxatiba) built over monazite sands were surveyed in detail by Roser and Cullen [R3]. Guarapari is a community of 12 000 people which receives an influx of about 30 000 vacationers every summer. In that town, the absorbed dose rates in air were found to range from 10^{-6} to 2 10^{-6} Gy h^{-1} in the streets and up to 2 10^{-5} Gy h^{-1} over selected spots on the beach [P3, R3]. Cullen [C1] by means of thermoluminescent dosimeters distributed to 317 inhabitants of Guarapari determined the average absorbed dose rate from external terrestrial irradiation (indoors plus outdoors) to be 6.3 10^{-7} Gy h^{-1}, with a range of 1 10^{-7} to 3.2 10^{-6} Gy h^{-1}.

25. Meaipe is a fishing village of about 3000 people, situated 50 km to the South of Guarapari, where the radiation environment is similar: the outdoor average absorbed dose rate in air is about 10^{-6} Gy h^{-1} with levels up to 10^{-5} Gy h^{-1} [P2]. In Cumuruxatiba, the average level is 5 10^{-7} Gy h^{-1} [R3].

26. In the state of Minas Gerais, two volcanic regions have been intensively studied, Poços de Caldas and Araxá-Tapira. There is a hill near the city of Poços de Caldas where absorbed dose rates in air of up to 2.8 10^{-5} Gy h^{-1} have been reported. However, this hill is small and uninhabited. In Araxá-Tapira, absorbed dose rates in air up to 4 10^{-6} Gy h^{-1} have been measured.

27. Quantitative information on the outdoor absorbed dose rates in air in other areas of high natural radiation levels is very limited. It is worth noting that in the city of Ramsar, Iran, absorbed dose rates in air ranging from 7 10^{-7} to 5 10^{-5} Gy h^{-1} have been measured within an area of a few square kilometres, characterized by the presence of ^{226}Ra-rich spring water [K3].

3. Exposure indoors

28. Knowledge of radiation levels in buildings is important in the assessment of population exposure, as most individuals spend a large portion of their time indoors. Table 3 summarizes the results obtained in the few large scale surveys of indoor exposure that have been reported. As the number of country-wide indoor surveys is relatively small compared to those conducted outdoors, the average absorbed dose rate in air indoors has been estimated from the outdoor value using an indoors to outdoors ratio.

29. The relationship between the indoor and the outdoor absorbed dose rates depends essentially on the type of building material used and on its origin. The building materials act as sources of radiation and also as attenuators of outdoor radiation. In wooden and prefabricated 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 is generally lower indoors than outdoors. The indoors to outdoors ratios presented in Table 3 range from 0.7 to 1.0 for wooden and prefabricated houses.

30. In massive houses made of bricks, 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. If they are of local origin, as is frequently the case, it may generally be assumed that the concentrations of natural radionuclides in the building materials are equal to those in the soil or the pavement surrounding the dwelling. Under these circumstances, it may be expected that the value of the indoors to outdoors ratio of the absorbed dose rates in air lies between 1 and 2, as the result of the change in source geometry and of the presence of doors and windows.

31. Calculations taking into account the thickness and the dimensions of the walls yielded ratios of 1.35 for typical brick dwellings and 1.48 for concrete buildings [K11], which are in good agreement with the results obtained in the extensive survey conducted in the Federal Republic of Germany [D2] and also with the large number of data from Norway [S6, S7] and Austria [T2]. In order to obtain a representative value of the indoor absorbed dose rate in air, the indoor to outdoor

ratios should be weighted according to the relative number of dwellings made of wood, brick or concrete. In Annex B of its 1977 report [U1], the Committee estimated the overall ratio to be about 1.2, which figure is also adopted in this Annex. This figure, combined with an average outdoor absorbed dose rate in air of $5\ 10^{-8}$ Gy h^{-1}, yields an indoor absorbed dose rate in air, averaged over the world, of $6\ 10^{-8}$ Gy h^{-1}. It is recognized that this figure is lower than the population-weighted average absorbed dose rates in air reported for a few countries (Table 3). It is felt however that these countries being all located in the northern part of Europe are not representative of the world-wide situation. More information would be required in order to provide a better estimate.

4. Annual effective dose equivalents from gamma terrestrial radiation

32. The most appropriate average value of the quotient of effective dose equivalent rate to absorbed dose rate in air appears now to be 0.7 for environmental exposures to gamma rays of moderate energy (see Annex A, paragraph 27). This value applies equally to males and females, and to the indoor and outdoor environments. Taking the outdoor occupancy factor to be 0.2, the annual effective dose equivalent from outdoor terrestrial gamma radiation is found to be

$$5\ 10^{-8}\,(\text{Gy h}^{-1}) \times 0.7\,(\text{Sv Gy}^{-1}) \times 8760\,(\text{h a}^{-1}) \times \times\ 0.2 = 6.1\ 10^{-5}\ \text{Sv}.$$

As to indoor exposure, using an occupancy factor of 0.8, the annual effective dose equivalent would be

$$6\ 10^{-8}\,(\text{Gy h}^{-1}) \times 0.7\,(\text{Sv Gy}^{-1}) \times 8760\,(\text{h a}^{-1}) \times \times\ 0.8 = 2.9\ 10^{-4}\ \text{Sv}.$$

33. The total (outdoors plus indoors) annual effective dose equivalent from terrestrial radiation, averaged over the world's population, would thus lie between $3\ 10^{-5}$ and $4\ 10^{-4}$ Sv. For the purpose of this report a representative value of $3.5\ 10^{-4}$ Sv has been adopted. From information contained in Annex B of the 1977 report of UNSCEAR [U1], 95% of the world population would thus receive annual effective dose equivalents in the range from about $2\ 10^{-4}$ to $5\ 10^{-4}$ Sv. In addition to the gamma radiation, the beta rays emitted by the naturally-occurring radionuclides contained in the soil and air contribute to a small extent to the effective dose equivalent from terrestrial radiation. According to O'Brien [O5], the annual effective dose equivalent resulting from beta radiation would be about $7\ 10^{-6}$ Sv. The radon and thoron decay products present in air contribute also to the total effective dose equivalent from external gamma radiation to a small extent [B2, O5].

II. INTERNAL IRRADIATION

34. Radioactive nuclides occurring in the biosphere enter the human body through ingestion and inhalation. The absorbed doses from internal exposure in lungs, gonads, red bone marrow, bone lining cells and other tissues will be estimated as well as the effective dose equivalent. For all radionuclides considered, ^{7}Be and ^{22}Na excepted, the absorbed doses are derived from measurements of the concentrations, in body organs or tissues, of the radionuclide concerned or of the most abundant stable isotope of the element. As discussed in Annex A, the conversion from the activity concentrations in tissues to the absorbed dose rates is based on ICRP models [I1].

A. COSMOGENIC RADIONUCLIDES

35. Very little of the dose from natural background is contributed by the cosmogenic radionuclides. Of the many nuclides produced by cosmic rays, only ^{3}H, ^{7}Be, ^{14}C and ^{22}Na contribute appreciably to the dose. The production and distribution of these nuclides in the environment is presented in Table 4, while Tables 5 and 6 show the resulting annual tissue doses in man.

1. Tritium

36. The major source of natural tritium is the atmosphere, where it is formed mainly from the interaction of cosmic-ray neutrons with nitrogen and oxygen. About 99% of the ^{3}H inventory, which is taken to be $1.3\ 10^{18}$ Bq is converted to tritiated water (HTO) and participates in the normal water cycle. Activity concentrations of surface waters, measured before nuclear explosions began, were found to be in the range 200–900 Bq m^{-3} for continental waters and about 100 Bq m^{-3} for ocean waters [K5]. In this report, the average activity concentration of natural tritium in continental surface waters is taken to be 400 Bq m^{-3}. Tritium enters food crops in the form of HTO and is partly incorporated into organic matter. Therefore, tritium in the diet can be in the form of HTO and of organic compounds. As the environment has been contaminated with artificial tritium since the early 1950s, there is no direct measurement of the natural tritium concentration in human tissues and the doses from natural tritium have to be estimated on the basis of indirect evidence.

37. In this Annex, as in Annex B of the 1977 report of UNSCEAR [U1], the absorbed dose rates due to natural tritium have been estimated by assuming that the specific activities of ^{3}H in body tissues are the same as those in the continental surface waters before nuclear explosions began; the annual absorbed doses obtained in that way are of the order of 10^{-8} Gy in all tissues (Table 5).

2. Beryllium-7

38. Environmental concentrations of ^{7}Be in the temperate zones are about 3000 μBq m^{-3} in surface air [K9] and 700 Bq m^{-3} in rainwater [A2]. The main pathway to man would be the ingestion of leafy vegetables, resulting in an annual intake of about 50 Bq [N4]. The tissue absorbed doses calculated using ICRP dosimetry [I1] are found to be 12 μGy in the walls of the lower large intestine and somewhat lower in the other tissues (Table 6). The annual effective dose equivalent would be about 3 μSv.

3. Carbon-14

39. Natural ^{14}C is produced in the upper atmosphere by the reaction ^{14}N(n,p)^{14}C induced by slow cosmic-ray neutrons. The specific activity in biological carbon, as measured in wood samples of trees grown in the nineteenth century, was 227 ± 1 Bq kg^{-1} of carbon [T1], corresponding to an atmospheric inventory of 140 PBq.

During the present century the specific activity of ^{14}C in air has decreased due to the diluting effect of releases into the atmosphere of carbon dioxide from the burning of fossil fuels; this is known as the Suess effect [S3].

40. In its 1977 report [U1], UNSCEAR estimated the world's inventory of natural ^{14}C to be about 60 times the amount found in the atmosphere, leading to a value of approximately 8500 PBq, corresponding to a production rate of 1 PBq a^{-1}.

41. Taking the natural specific activity of ^{14}C in the body to be 227 Bq kg^{-1} of carbon, and using the concentrations of carbon in body tissues indicated by ICRP for the Reference Man [I2], the annual absorbed doses in tissue are found to be in the range from 5 to 24 μGy (Table 5). The annual effective dose equivalent would be 12 μSv. This value is in agreement with the figure derived from ICRP [I1], assuming an annual intake of 93 kg of carbon [I2].

4. Sodium-22

42. The annual absorbed doses from ^{22}Na have been calculated on the basis of an annual intake by ingestion of 50 Bq [N4] and using ICRP dosimetry [I1]. The annual absorbed doses in tissues are in the range of 0.1 to 0.3 μGy (Table 6), corresponding to an annual effective dose equivalent of about 0.2 μSv. Even though the production rate and the atmospheric concentration of ^{22}Na are very small (Table 4), the estimated annual absorbed doses arising from the incorporation of that radionuclide (Table 6) are higher than those due to ^{3}H (Table 5) because of the metabolic behaviour of sodium and of the decay properties of ^{22}Na.

B. PRIMORDIAL RADIONUCLIDES

43. The primordial radionuclides include those belonging to the ^{235}U, ^{238}U and ^{232}Th series and some other nuclides, among which only ^{40}K and ^{87}Rb are significant sources of radiation.

1. Potassium-40

44. Potassium is an essential element, and is under close homeostatic control in the body. The average mass concentration for an adult male is about 2 g of potassium per kg of body weight [A1, K10]. The isotopic ratio of ^{40}K is 1.18 10^{-4} and the average activity concentration of ^{40}K in the body is about 60 Bq kg^{-1}. The distribution of potassium in various tissues and organs of the body [K10] and the corresponding absorbed dose rates are presented in Table 7. The highest annual absorbed dose (270 μGy) is received in the red bone marrow. The annual effective dose equivalent is estimated to be 180 μSv.

45. The variation of the mass of potassium in the total body with age and sex has been investigated by several groups. In the United States during the period 1956–1961, total body potassium was determined in about 3000 subjects who ranged from less than one year to 79 years of age [A4, I2]. The results of this study show that the concentrations of potassium in the total body increase from birth to about 10 years for girls and 18 years for boys, when they reach estimated average values of about 2.1 and 2.3 g kg^{-1}, respectively; the concentrations then decrease rather sharply until the age of 20 and more gradually later on [A4, I2]. Actually the variation with age and sex of the concentration of potassium in the total body reflects the amount of relatively potassium-free adipose tissue which is present with the "lean body mass" in the total body at different ages [I2]. Similar results were found by Oberhausen [O8] in the Federal Republic of Germany in a study involving 12 000 subjects. The relationship between the mass of potassium in the total body and the age was found to be linear for boys and girls under 12 [S10]. With respect to adults, Andrasi and Beleznay [A1], from measurements on about 600 subjects derived the following linear relationships between the quotient of the mass of potassium in the body C, in g kg^{-1}, for the whole body and the age A, in years:

$$C = 2.34 - 0.0110\ A \text{ for males and}$$

$$C = 1.99 - 0.0109\ A \text{ for females.}$$

2. Rubidium-87

46. Very little is known about the behaviour of rubidium in man's environment. From the mass concentrations of rubidium in the ICRP Reference Man [I2], the average activity concentration of ^{87}Rb in the body would be 8.5 Bq kg^{-1}. Table 7 presents the assumed distribution of rubidium in the body and the resulting absorbed dose rates from ^{87}Rb. Bone lining cells receive the highest annual dose (14 μGy). The annual effective dose equivalent is estimated to be about 6 μSv.

3. Uranium-238 series

47. Uranium-238 is the head of a series of 15 principal nuclides (Figure III). In its 1972 and 1977 reports [U1, U2], the Committee has classified the ^{238}U series in subseries in which the activity of the precursor controls to a large degree the activities of the decay products. The ^{238}U series has been divided into: (1) $^{238}U \rightarrow {}^{234}U$; (2) ^{230}Th; (3) ^{226}Ra; (4) $^{222}Rn \rightarrow {}^{214}Po$, which is discussed in detail in Annex D; (5) $^{210}Pb \rightarrow {}^{210}Po$. For each subseries, the intakes by inhalation and by ingestion as well as the concentrations in bone and in soft tissues will be estimated. The conversion from the activity concentrations in bone and in soft tissues to the absorbed doses is based on the models described in ICRP Publication 30 [I1].

(a) Uranium-238 subseries (^{238}U, ^{234}Th, ^{234m}Pa, ^{234}U)

48. In this Annex, uranium is assumed to consist of ^{238}U in radioactive equilibrium with ^{234}Th, ^{234}Pa and ^{234}U, so that 1 kg of uranium contains 12 MBq of each of the four radionuclides. The contribution of ^{235}U and its decay products to the total dose from natural background has been neglected.

49. In the atmosphere, the main natural source of uranium has been assumed to be the resuspension of dust particles from the earth. Assuming a dust loading of about 50 μg m^{-3} in surface air of populated areas, and taking an average ^{238}U activity concentration in soil of 25 Bq kg^{-1} (Table 1), the activity concentration in ground level air is estimated to be about 1.2 μBq m^{-3}. Measurements of the activity concentration in ground level air, as for example in Munich (Federal Republic of Germany) confirm the validity of the assumption

[J4]. The corresponding annual intake by adults through inhalation is approximately 0.01 Bq (Table 8).

50. The annual dietary intake of ^{238}U has been found to be about 5 Bq in areas of "normal" natural activity [U1] and the contribution of drinking water is generally negligible in comparison. However, it should be mentioned that very high concentrations of uranium in tap water have been reported. In France [R4, R5] and in the USSR [B6], activity concentrations as high as 1.0 and 2.6 kBq m^{-3}, respectively, have been observed. In Helsinki, Finland, activity concentrations of the order of 100 kBq m^{-3} have been measured in several wells, the highest concentration being about 200 kBq m^{-3} [K7]. According to the authors [K7], the very high concentrations of uranium in the water of those wells are probably caused by small, localized uranium-rich deposits.

51. Measured values of the activity concentrations of ^{238}U in bone of adults who have lived in areas with "normal" dietary levels are in the range of 100 to 200 mBq kg^{-1}, yielding an activity in bone of about 0.7 Bq [J4, U1]. In soft tissues, the activity concentrations of ^{238}U cover a much broader range. The measured values lie between 1 and 10 mBq kg^{-1} for most of the soft tissues and between 10 and 80 mBq kg^{-1} for kidneys [J4]. Assuming that the distribution of the activity in the body is 70% in bone and 30% in soft tissue [J4], and that the levels in kidney are 10 times higher than those in other soft tissues, the average activity concentrations are found to be about 150 mBq kg^{-1} in bone, 50 mBq kg^{-1} in kidneys and 5 mBq kg^{-1} in the other soft tissues. The resulting annual absorbed doses vary from $2\ 10^{-8}$ Gy in lung to $3\ 10^{-6}$ Gy in bone lining cells (Table 9).

(b) Thorium-230

52. The activity intake of ^{230}Th through inhalation, estimated in the same way as for ^{238}U, is about 0.01 Bq a^{-1}. There is no information on the dietary intake of ^{230}Th. However, the activity ingested is probably a negligible contribution to the body content of ^{230}Th because of the very low absorption of thorium through the gastro-intestinal tract.

53. Thorium is a bone seeker which has a long residence time in the skeleton and is assumed to remain on the bone surfaces [I1]. The distribution of ^{230}Th in human tissues has been investigated by Wrenn and his collaborators [S9, W1, W4]. In samples of two population groups living in Colorado and in Washington, D.C., the highest concentrations were in general measured in the lymph nodes, followed by bone, lung, kidneys, liver and spleen. The mass of bone being much greater than that of the lymph nodes, most of the thorium body content was found in the skeleton (about 70%). As thorium has a long residence time in the skeleton, the concentration of ^{230}Th in bone increases continuously with age for a constant rate of intake. On the basis of the available measurements [S9, W1, W4], it seems that a typical activity of ^{230}Th in bone is 140 mBq, resulting in activity concentrations of approximately 20 mBq kg^{-1} in cortical bone and 70 mBq kg^{-1} in trabecular bone. This is on the assumption that the deposit of thorium is proportional to the bone area. In soft tissues, representative values of the activity concentrations could be 300 mBq kg^{-1} in lymph nodes, 20 mBq kg^{-1} in lungs, 10 mBq kg^{-1} in kidneys, 7 mBq kg^{-1} in liver and 0.3 mBq kg^{-1} in the other soft tissues. The corresponding annual absorbed doses are presented in Table 10. The annual effective dose equivalent is estimated to be about 7μSv.

(c) Radium-226

54. For inhalation, as in the case of uranium and thorium, the main natural source of radium in the air at ground level is assumed to be the resuspension of soil particles; this corresponds to a calculated activity intake of about 0.01 Bq a^{-1}.

55. Food is a much more important source of radium for intake and blood uptake than is inhalation. The average annual dietary intake of ^{226}Ra in areas of normal radiation background is about 15 Bq (see Annex B in the UNSCEAR 1977 report [U1]). The contribution of drinking water is generally small when the drinking water supplies are drawn from surface waters. However, activity concentrations of 0.1 Bq l^{-1} are not exceptional in well and mineral waters [K12, K13, M7, P7, R4, R5]. In France, for example, an activity concentration of 2.7 Bq l^{-1} has been measured in a spring used as drinking water [R4, R5]. The population groups drinking exclusively those waters are expected to derive most of their ^{226}Ra intake from the water.

56. Two well-known populated areas with high concentrations of uranium in their soil are located along the coast of Kerala in India and in the Araxá-Tapira region in Brazil. The estimated average annual intake of ^{226}Ra of the Indian population along the Kerala coast is 40 Bq [C3, M1]. In Brazil, a survey in the Araxá-Tapira region showed that, out of a population of 1670 people living in and around the radioactive anomalies of Barreiro and Tapira, only 196 individuals ingested alpha emitters at a level 5 times or more than that of a similar group living in Rio de Janeiro. The annual ^{226}Ra intake of those individuals ranged from 140 to 540 Bq [P4].

57. When radium is taken into the body, its metabolic behaviour is similar to that of calcium, and an appreciable fraction is deposited in bone [E2]. About 70–90% of the radium in the body is contained in bone [I3], the remaining fraction being distributed approximately uniformly in soft tissues. Fisenne et al. [F1] have summarized the available data from 26 countries on measured activity concentrations of ^{226}Ra in human bone. The 26 countries sampled have $1.4\ 10^9$ persons and thus represent about 30% of the world population. The population-weighted distribution was found to have a median of 850 mBq per kg of calcium (corresponding to 170 mBq per kg of bone and to 850 mBq in the skeleton) and a geometric standard deviation of 1.6. If the fraction of ^{226}Ra distributed in the soft tissues is taken to be 17%, as given in ICRP publication 20 [I3], the average activity concentration in human soft tissues is found to be 2.7 mBq kg^{-1}.

58. The annual absorbed doses in tissues have been calculated using the same assumptions as in Annex B of the 1977 report, namely, that an average retention factor of 0.33 applies to ^{222}Rn in the skeleton and also, conservatively, in soft tissues; and that the concentration of radium and its decay products is uniform over the total mass of mineral bone. The results are presented in Table 11. The annual effective dose equivalent resulting from ^{226}Ra intake in "normal" areas is found to be about 7 μSv.

59. Data on the activity of radium in the skeleton of people living in the high radiation areas of Brazil and India are very scarce. In Brazil, the mean ^{226}Ra concentration in the teeth of the population living in the Araxá-Tapira region has been estimated as approximately 3 Bq kg^{-1} of ash, which corresponds to an activity in the skeleton of about 8 Bq, assuming that the concentration in teeth is the same as that in bone. In India, the analysis of a femur yielded a ^{226}Ra concentration per unit mass of ash of 5 Bq kg^{-1}, which corresponds to a skeletal activity of about 15 Bq [C3].

(d) Radon-222, and its short-lived decay products (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po)

60. Man is exposed to ^{222}Rn (radon) and to its short-lived decay products mainly by inhalation. Mean annual values of radon concentration in outdoor air vary between 0.1 and 10 Bq m^{-3}. Over land, a reasonable estimate of the average concentration at ground level is 3 Bq m^{-3}; taking the equilibrium factor to be 0.6, the average equilibrium equivalent concentration of radon in outdoor air at ground level is estimated to be 1.8 Bq m^{-3}.

61. In temperate latitudes, the average equilibrium equivalent concentration of radon in air is several times higher indoors than outdoors. The mean values of the indoor equilibrium equivalent radon concentrations in different countries cover the range from 5 to 25 Bq m^{-3}, with the exception of Sweden, where the average value is 60 Bq m^{-3}. For the total population in the temperate regions of the world, 15 Bq m^{-3} seems to be an appropriate mean indoor equilibrium equivalent concentration.

62. Using the dose conversion coefficients derived in Annex D, the annual effective dose equivalents corresponding to the average equilibrium equivalent concentrations of radon outdoors and indoors in temperate latitudes are estimated to be 0.92 mSv from indoor exposure and about 0.06 mSv from outdoor exposure, giving a total of about 1 mSv for inhaled ^{222}Rn daughters.

63. For equatorial regions no measurements are available. Because of the different domestic conditions, the indoor level of radon daughters in this region might be considerably lower than in temperate regions. For large population groups this level will be comparable with the normal outdoor level, leading to an annual effective dose equivalent of about 0.2 mSv. Taking into account that about two thirds of the total world population is living in temperate regions, a global mean value of about 0.8 mSv per year—averaged over all age groups—from inhaled ^{222}Rn daughters should be expected.

64. Table 12 summarizes the estimated equilibrium equivalent concentrations of ^{222}Rn and the corresponding annual effective dose equivalents. A detailed treatment of the exposures to ^{222}Rn and its daughters is provided in Annex D.

(e) Long-lived decay products of ^{222}Rn (^{210}Pb, ^{210}Bi, and ^{210}Po)

65. For inhalation, the main source of ^{210}Pb and ^{210}Po in the atmosphere is ^{222}Rn emanation from the ground. In the mid-latitudes of the northern hemisphere, the average concentration of ^{210}Pb in surface air has been estimated to be 0.5 mBq m^{-3} [J2]. The $^{210}Po/^{210}Pb$ activity ratio in ground level air being about 0.2 [J3], the activity concentration of ^{210}Po is about 0.1 mBq m^{-3}. Assuming that the atmospheric concentrations are the same indoors and outdoors, the annual intakes of non-smokers would thus be 4 Bq of ^{210}Pb and 0.8 Bq of ^{210}Po. Cigarette smoking will lead to an increase in the intake of ^{210}Pb and ^{210}Po through inhalation [P5].

66. Consumption of food is usually the most important route by which ^{210}Pb and ^{210}Po enter the human organism. For the areas of normal intake, a value of 40 Bq was taken in Annex B of the 1977 report [U1] as representative of the annual intake of ^{210}Pb and ^{210}Po. Recent estimates for the populations of India and of Italy are in good agreement with that figure [C7, L7]. It should be noted however that lower values are consistently obtained for the populations of the United States [H9, H10]. High concentrations of ^{210}Po are observed in the edible portions of aquatic organisms, for which it is well established that the $^{210}Po/^{210}Pb$ activity concentration ratio is greater than 1 [C4]. The ^{210}Po concentrations in the muscles of fish and in molluscs are approximately 0.7 and 20 Bq kg^{-1}. The intakes of ^{210}Pb and ^{210}Po in populations consuming large proportions of seafood are therefore expected to be higher than those of populations with other types of diet.

67. A well-documented case of elevated intake is that of the tens of thousands of individuals living on reindeer or caribou meat in the arctic and sub-arctic regions of the northern hemisphere [H10, P8]. Their main food is the meat of these animals, which contains unusually high concentrations of ^{210}Po because in the winter they graze on lichens which accumulate ^{210}Pb and ^{210}Po. The annual intakes of ^{210}Pb and ^{210}Po by the populations living on reindeer or caribou meat are about 140 Bq for ^{210}Pb and about 1400 Bq for ^{210}Po. Another documented case of elevated intake relates to an uranium-rich area of Western Australia, where the annual intake of ^{210}Pb from the carcasses of local sheep and kangaroos is about 100 Bq and from the offal about 300 to 3000 Bq [W5].

68. In view of the short half-life of ^{210}Bi (5 d), the activity intakes of that radionuclide can be assumed to be the same as those of ^{210}Pb. Precise values are of no interest for the purpose of this Annex as ^{210}Bi can be assumed to be in radioactive equilibrium with ^{210}Pb in the body tissues so that the absorbed doses from ^{210}Bi mainly arise from the intake of ^{210}Pb and not from the intake of ^{210}Bi itself.

69. Concerning distribution in man, lead is a bone seeker which is found incorporated in bone mineral, from where it seems to be eliminated by long-term skeletal remodelling [H6, L6]. About 70% of the body content of ^{210}Pb is found in the skeleton [J2]. In continental areas of the northern latitudes, a typical activity concentration of ^{210}Pb in bone would be 3 Bq kg^{-1} [U1]. The skeletal activity would thus be 15 Bq and the activity in soft tissues would be 6.4 Bq distributed relatively uniformly throughout the body (Table 13).

70. Polonium, in contrast to all the other natural alpha emitters, is not a bone seeker but is rather distributed in soft tissues after intake. Therefore, the greatest part of the ^{210}Po bone activity arises from the decay of deposited ^{210}Pb [H7, W2]. Average measured ratios of ^{210}Po and ^{210}Pb activity concentrations in bone range

from 0.5 to 1.1 [B7, H4, K8, L5, M2]. A value of 0.8 is assumed to be representative for the purposes of this Annex. The ^{210}Po concentration in bone would thus be about 2.4 Bq kg^{-1} for the populations living in continental areas in temperate regions of the northern hemisphere.

71. In soft tissues, the activity of ^{210}Po is about the same as that of ^{210}Pb. Typical concentrations of ^{210}Pb and ^{210}Po in the gonads are about 0.2 Bq kg^{-1} [B7, L5, B8]. In lungs the concentrations in non-smokers are around 0.1 Bq kg^{-1} for ^{210}Po and 0.2 Bq kg^{-1} for ^{210}Pb [B7, H5]. In red bone marrow, Ladinskaya et al. [L5] measured a ^{210}Pb concentration of 0.14 Bq kg^{-1} and a ^{210}Po/^{210}Pb activity ratio of 0.8. Although in most of the soft tissues the ^{210}Po/^{210}Pb activity concentration ratio is about 1, it is clearly greater than 1 in a few organs such as the liver and kidney. The excess ^{210}Po is probably taken up directly from food and would be partly attributable to a higher rate of incorporation for ^{210}Po than for ^{210}Pb in those organs [J2]. The additional intake due to smoking leads to increased concentrations of ^{210}Pb and ^{210}Po in organs and tissues. As expected, it is in the lung that the increases are most clearly marked. The concentrations in that organ exceed on the average the levels found in non-smokers by factors of about 1.5 for ^{210}Pb and 3 for ^{210}Po [B7, H7, H10, P5, R2]. The figures given in Table 13 correspond to non-smokers.

72. With respect to the arctic and sub-arctic populations, measurements carried out on the blood, placenta and bone tissues of inhabitants of the northern regions who consume reindeer or caribou meat regularly show levels higher than those in the populations of the temperate latitudes. The increase is by a factor of 2 to 3 for ^{210}Pb in all tissues and for ^{210}Po in bone tissues and by a factor of about 10 for ^{210}Po in soft tissues [H10, K8, P8].

73. The absorbed doses from the ^{210}Pb subseries depend mainly on the highly energetic alpha particles of ^{210}Po, as the contribution from the beta emissions of ^{210}Pb and ^{210}Bi amounts to about 10% of the total. Table 13 presents the estimated annual absorbed doses from ^{210}Pb, ^{210}Bi and ^{210}Po for non-smokers in areas of normal dietary intake. The annual effective dose equivalent arising from the total intake of ^{210}Pb, ^{210}Bi and ^{210}Po would be about 130 μSv. The corresponding figure for the populations living on reindeer or caribou meat would be about 10 times higher.

4. Thorium-232 series

74. Thorium-232 is the head of a series of 12 nuclides (Figure IV). The ^{232}Th and the ^{238}U series present strong similarities: they include isotopes of the same elements (radium, radon, lead, bismuth, polonium) and contain a large proportion of α-emitters. The main difference between the two series is that ^{232}Th is the only very long-lived radionuclide in its chain.

75. The ^{232}Th series has been divided into three subseries: (a) ^{232}Th itself; (b) ^{228}Ra → ^{224}Ra; (c) ^{220}Rn → ^{208}Pb, which is discussed in detail in Annex D. The three subseries will be considered in turn.

(a) Thorium-232

76. The activity concentration of ^{232}Th in soil is estimated to be on average the same as that of ^{238}U and its decay product ^{230}Th (25 Bq kg^{-1}, see Table 1). Since the main natural source of ^{232}Th in air at ground level is assumed to be the resuspension of soil particles, the annual activity intake of ^{232}Th through inhalation, estimated in the same way as for ^{238}U and ^{230}Th, is also about 0.01 Bq. As in the case of ^{230}Th, the contribution of the ingestion pathway to the body content of ^{232}Th can be probably neglected because of the very low absorption of thorium through the gastro-intestinal tract.

77. The distribution of ^{232}Th in human tissues was mainly investigated by Wrenn and his collaborators [S9, W1, W4] in their studies on the comparison of uranium, thorium and plutonium in man. In comparison with ^{230}Th, the activity concentrations of ^{232}Th were found to be lower by a factor of about 10. On the basis of those measurements, the body content of ^{232}Th would be about 80 mBq, 60% of which is in the skeleton. The activity concentrations adopted in this Annex are presented in Table 14, along with the resulting annual absorbed doses. The annual effective dose equivalent is calculated to be about 3 μSv.

(b) Radium-228 subseries (^{228}Ra, ^{228}Ac, ^{228}Th, ^{224}Ra)

78. Radium is much more available to plants and to animals than ^{232}Th so that the activity concentrations of ^{228}Ra in man are mostly due to the dietary intake of ^{228}Ra itself and not to the decay of ^{232}Th in the body. Radium-228 can thus be considered to be the head of a subseries in which ^{228}Th (1.9 a) and ^{224}Ra (3.6 d), as alpha emitters, are the most important contributors to the dose.

79. The annual activity intake arising from inhalation of resuspended soil particles is estimated to be about 0.01 Bq, as for all precursors of radon isotopes (Table 8). However, food consumption is a much more important source of ^{228}Ra intake than inhalation. In areas of normal radiation background the annual intake is about 15 Bq (Table 8).

80. In the high-background area along the Kerala coast in India, the estimated average annual intake of ^{228}Ra is about 2000 Bq [M1] whereas a survey conducted in the Araxá-Tapira region of Brazil showed that about 200 individuals ingested ^{228}Ra at a rate of between 700 and 3000 Bq a^{-1} [U1].

81. Radium and thorium are bone seekers. In Annex B of its 1977 report [U1], the Committee estimated the average ^{228}Ra activity concentrations in bone and in soft tissues to be 90 mBq kg^{-1} and 4 mBq kg^{-1}, respectively, in areas of normal background radiation. With respect to ^{228}Th, Wrenn and Singh [S9, W4] showed that approximately 80% of the body content (about 300 mBq) is in bone. The values of the activity concentrations adopted in this Annex are shown in Table 15; they are mainly based on the measurements of Wrenn and Singh [S9, W4].

82. The annual absorbed doses in tissues have been calculated using the same assumptions as in Annex B of the 1977 report [U1], namely, that complete retention in the body of the ^{220}Rn activity arises from decay of ^{224}Ra; and that the concentrations of ^{228}Ra and its decay products over the total mass of bone is uniform. The results are presented in Table 15. The corre-

sponding annual effective dose equivalent for the subseries is found to be about 13 μSv.

(c) Radon-220 and its decay products (^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po, ^{208}Tl)

83. As is the case with ^{222}Rn, inhalation is the major pathway through which man is exposed to ^{220}Rn (thoron) and to its short-lived decay products. A detailed treatment of the sources of exposure to ^{220}Rn is provided in Annex D. In outdoor air, the equilibrium equivalent concentration of ^{220}Rn is about 0.2 Bq m^{-3}. With respect to indoor air, very few measurements of ^{220}Rn daughters have been reported, if compared with the available information on ^{222}Rn daughters. However, the simultaneous measurements of ^{222}Rn and ^{220}Rn daughters in houses in the Federal Republic of Germany and in the United Kingdom indicate a ratio of about 20 between equilibrium equivalent ^{222}Rn concentration and the equilibrium equivalent ^{220}Rn concentration. Applying this factor it can be concluded that the mean value of the indoor equilibrium equivalent ^{220}Rn concentration in different countries should be in the range 0.2–1.2 Bq m^{-3}. For the total population in temperate regions of the world a mean value of about 0.7 Bq m^{-3} should be expected. Taking into account the dose conversion coefficients for ^{220}Rn daughters given in Annex D, the annual effective dose equivalents corresponding to the average equilibrium equivalent concentrations of radon indoors and outdoors in temperate latitudes are estimated to be 0.20 mSv from indoor exposure and about 0.02 mSv from outdoor exposure, giving a total of 0.22 mSv for inhaled ^{220}Rn daughters.

84. For equatorial regions no measurements are available. Because of the different domestic conditions, the indoor levels of ^{220}Rn daughters might be considerably lower than in temperate regions. For large population groups this level will be comparable with the normal outdoor equilibrium equivalent concentration, leading to an annual effective dose equivalent in equatorial regions of 0.08 mSv from inhalation of ^{220}Rn daughters. Taking into account that about two thirds of the total world population is living in temperate regions, a global mean value of the annual effective dose equivalent of about 0.17 mSv from inhalation of ^{220}Rn daughters should be expected. Table 16 summarizes the estimated average equilibrium equivalent concentrations of ^{220}Rn and the corresponding annual effective dose equivalents.

III. RECAPITULATION

85. Table 17 summarizes the contributions of natural sources to the radiation exposure of human populations living in areas of normal radiation background. The exposures refer to adult persons and are expressed in terms of effective dose equivalent in order to facilitate the comparison of the various sources of radiation. The effective dose equivalent from all internal sources is estimated to be about twice that from external irradiation. Among the various contributors to the internal irradiation, the short-lived decay products of ^{222}Rn are by far the most important as they are responsible for about 60% of the effective dose equivalent from internal emitters. Then follow, by decreasing order of importance, ^{40}K (13%), the short-lived decay products of ^{220}Rn (13%), and ^{210}Pb-^{210}Po (8%). With regard to external irradiation, the effective dose equivalent from cosmic rays is slightly lower than that from terrestrial radiation.

86. Significantly higher doses from external radiation are received by population groups living at high altitudes or in regions of high natural radioactivity. A number of population groups are exposed to elevated internal absorbed doses, such as the people living in houses with a low rate of ventilation or the caribou and reindeer eaters. The importance of the contribution of areas of high natural radiation to the global effective collective dose equivalent cannot yet be assessed. As a first approximation the global annual collective effective dose equivalent from natural radiation sources is estimated to be of the order of 10^7 man Sv.

87. From Table 17 a median annual effective dose equivalent of about 2 mSv from natural sources in areas of normal background results. This average value refers to the adult part of the population. For children the values of the annual effective dose equivalent, particularly for inhaled radon daughters, are higher than for adults. Estimates yield a mean annual effective dose equivalent from natural sources of about 3 mSv for children in the 0 to 10-year age group.

88. The available data, particularly on the relevant contributions from radon daughters and terrestrial gamma radiation, indicate that on a global scale the distribution function of the natural radiation exposure can be approximated in its central part by a normal or log-normal distribution. With this assumption a standard deviation of about 0.3 to 0.6 mSv can be estimated.

Table 1

Average activity concentration of potassium-40, uranium-238 and thorium-238 in soil and absorbed dose rate in air 1 m above the ground surface

Radionuclide or decay series	Dose rate per unit activity concentration in soil (10^{-10} Gy h^{-1} per Bq kg^{-1})	Average concentration in soil a/ (Bq kg^{-1})	Absorbed dose rate in air a/ (10^{-8} Gy h^{-1})
^{40}K	0.43	370 (100-700)	1.6 (0.4-3.0)
^{238}U	4.27	25 (10- 50)	1.1 (0.4-2.1)
^{232}Th	6.62	25 (7- 50)	1.7 (0.5-3.3)

a/ The typical range is given within brackets.

Table 2

Estimates of the average absorbed dose rate in air 1 m above ground level (based on country- and area-wide surveys)

Country or area	Average absorbed dose rate in air and range a/ (10^{-8} Gy h^{-1})	Number of measurements	Period of survey	Type of survey and instrumentation used	Ref.
Austria	4.3 (0.2-15)	> 1000	1970-1974	Ground survey in populated areas with a Geiger-Müller counter	[T2]
Denmark	3.8 (1.7-5.2)	14 sites	1978	Ground survey with an ionization chamber and a gamma spectrometer	[N5]
France	8.1 (0.9-29)	865	1978	Ground survey with thermolumi-nescent dosimeters (preliminary results)	[M3, M8]
German Dem.Rep.	9.4 (2.4-27)	1005	1965-1966	Ground survey with an ionization chamber	[O1]
Germany, Fed.Rep. of	5.3 (0.4-35)	24739	1973-1974	Ground survey with scintillation detectors	[C8, D2]
India	4.2 (normal areas)	35 sites	1965-1972	Analysis of soil samples by gamma spectrometry	[M4]
Ireland	4.2 (0-18)	264	1978	Ground survey with an ionization chamber	[M5]
Italy	5.7 (0.7-50)	1365	not indicated	Ground survey with an ionization chamber	[A3]
Japan	4.9 (0.5-10)	1127	1967-1977	Ground survey with an ionization chamber and scintillation detectors	[A3]
Norway	7.3 (2-110)	234	1976	Ground survey with an ionization chamber placed in a car	[S6]
Poland	3.7 (1.5-9)	352 sites	1975-1978	Ground survey with thermolumi-nescent dosimeters	[N6]
Romania	8.1 (3.2-21)	2372	not indicated	Analysis of soil samples by gamma spectrometry	[T3]
Switzerland	8.7	not indicated	1962	Ground survey with an ionization chamber	[H1]
United States	4.6 (1.3-10)	25 areas covered b/	1958-1963	Aerial survey with scintillation detectors	[O7]
Other Asia	6.9	26	1969	Analysis of soil samples by gamma spectrometry	[W3]

a/ The range is given within brackets.
b/ Inhabited by approximately 30 % of the country's population.

Table 3

Results of surveys of indoor absorbed dose rate in air due to gamma terrestrial radiation

Country	Period of survey	Number of dwellings	Type of building	Indoor average absorbed dose rate in air (10^{-8} Gy h^{-1})	Population-weighted average absorbed dose rate in air (10^{-8} Gy h^{-1})	Indoors to outdoors ratio	Population-weighted indoors to outdoors ratio	Ref.
Austria	1975-1978	1900	Brick	10.8	7.1		1.65	[T2]
			Concrete	8.1				
			Wood	7.5				
			Natural stone	10.9				
France (1)	1978	946	Various types	8.8		1.09		[M3]
(2)	1977-1979	1020	Various types	9.9		1.11		[B9]
German Dem.Rep.	1965-1966	667	Various types		7.4		0.78	[01]
Germany, Fed.Rep. of	1973-1974	29996	Solid	7.0	7.0	1.37	1.36	[D2]
			Frame	7.1		1.34		
			Prefabricated	4.0		0.94		
			Wood	4.5		1.02		
Norway	1963+1976	2026	Brick	11.9	9.5	1.60	1.12	[S6, S7]
			Concrete	10.5		1.42		
			Wood	7.1		0.95		
Poland	1978	49	Red Brick			1.2		[N6]
			Concrete			1.1		
			Building material containing blast furnace slag			1.8		
Sweden	1977	1189	Brick	9.2	9.6			[M6]
			Concrete	11.6				
			Aerated concrete	17.2				
			Wood	5.3				
United Kingdom	1959	501	Solid: sedimentary rock					[S8]
			- Dundee	7.6		1.07		
			- Edinburgh granite	6.8		1.24		
			- Aberdeen	9.7		0.82		
			- Aberdeenshire	9.4		1.17		
United States (1)	1971	110	Wood	3.9 a/		0.75		[L2]
(2)	1962	160	Wood			0.70		[L3]

a/ Median value.

Table 4

Data on naturally-occurring ^{3}H, ^{7}Be, ^{14}C, and ^{22}Na

Item	Radionuclide				Ref.
	^{3}H	^{7}Be	^{14}C	^{22}Na	
Half-life	12.3 a	53.6 d	5730 a	2.62 a	[L8]
Numbers of atoms produced per unit time and per unit area of the earth's surface ($m^{-2}s^{-1}$)					
Troposphere	840	270	11000	0.24	[L4]
Total atmosphere	2500	810	16000-25000	0.86	[L4,U1]
Global inventory (PBq)	1300	37	8500	0.4	[L4,U1]
Distribution as a percentage of inventory					
Stratosphere	6.8	60	0.3	25	[L4]
Troposphere	0.4	11	1.6	1.7	[L4]
Land surface and biosphere	27	8	4	21	[L4]
Mixed oceanic layers	35	20	2.2	44	[L4]
Deep ocean	30	0.2	92	8	[L4]
Oceanic sediments			0.4		[L4]
Activity concentration in surface air ($\mu Bq\ m^{-3}$)		3000		0.3	[K9]
Activity concentration in continental surface waters ($Bq\ m^{-3}$)	200-900				[B5,K5]
Specific activity in terrestrial biosphere ($Bq\ kg^{-1}$)			230		[S3]

Table 5

Estimated tissue concentrations and annual absorbed doses from ^{3}H and ^{14}C

Organ or tissue	Hydrogen			Carbon		
	Mass concentration of element ($g\ kg^{-1}$)	Activity concentration of ^{3}H ($Bq\ kg^{-1}$)	Annual absorbed dose (μGy) β	Mass concentration of element ($g\ kg^{-1}$)	Activity concentration of ^{14}C ($Bq\ kg^{-1}$)	Annual absorbed dose (μGy) β
Gonads	100	0.4	0.01	89	20	5.0
Lungs	99	0.4	0.01	100	23	5.7
Red bone marrow	100	0.4	0.01	410	93	24
Bone lining cells			0.01			22
Thyroid	100	0.4	0.01	105	24	5.9
Other tissues	105	0.4	0.01	230	52	13

Table 6

Absorbed doses in tissues from internal irradiation by ^{7}Be and ^{22}Na

Organ or tissue	Annual absorbed dose (μGy)	
	^{7}Be γ	^{22}Na β^{+},γ
Gonads	5.7	0.14
Breast		0.13
Lungs		0.12
Red bone marrow	1.2	0.22
Bone lining cells		0.27
Thyroid		0.12
Stomach wall		0.14
SI wall	5.4	0.15
ULI wall	7.3	
LLI wall	12	0.15
Remainder		0.10

Table 7

Average tissue concentrations in adult males and annual absorbed doses from ^{40}K and ^{87}Rb

Tissue or organ	Potassium			Rubidium		
	Mass concentration of element ($g\ kg^{-1}$)	Activity concentration of ^{40}K ($Bq\ kg^{-1}$)	Annual absorbed dose (μGy) β^{-},γ	Mass concentration of element ($mg\ kg^{-1}$)	Activity concentration of ^{87}Rb ($Bq\ kg^{-1}$)	Annual absorbed dose (μGy) β^{-}
Gonads (Testes)	2.1	64	180	20	18	10.0
Lungs	2.1	64	180	9.2	8.1	4.5
Red bone marrow	4.4	130	270	7.8	7.0	7.0
Bone lining cells			140			14.0
Thyroid	1.1	33	100	6.0	5.3	3.0
Other tissues	2.0	61	170	7.8	7.0	4.0

Table 8

Intakes in normal areas of ^{238}U, ^{232}Th and their decay products

Source	Annual intake (Bq)	
	Inhalation	Ingestion
^{238}U series		
^{238}U	0.01	5
^{234}Th	0.01	5
^{234}Pa	0.01	5
^{234}U	0.01	5
^{230}Th	0.01	-
^{226}Ra	0.01	15
^{210}Pb	4	40
^{210}Po	0.8	40
^{232}Th series		
^{232}Th	0.01	-
^{228}Ra	0.01	15
^{228}Ac	0.01	15
^{228}Th	0.01	15

Table 9

Average activity concentrations in tissues and annual absorbed doses resulting from internal irradiation by radionuclides from the uranium-238 subseries

Organ or tissue	Activity concentration of ^{238}U a/ (mBq kg^{-1})	Annual absorbed doses (10^{-7} Gy)			
		^{238}U α	^{234}Th β,γ	^{234m}Pa β,γ	^{234}U α
Gonads	5	1.1	0.02	0.2	1.2
Breast	5	1.1	0.02	0.2	1.2
Lungs	5	1.1	0.02	0.2	1.2
Cortical bone	150				
Trabecular bone	150				
Red bone marrow	5	2.1	0.11	1.4	2.4
Bone lining cells		17	0.34	4.3	20
Thyroid	5	1.1	0.02	0.2	1.2
Kidneys	50	11	0.15	2.1	12
Other tissues	5	1.1	0.02	0.2	1.2

a/ ^{238}Th, ^{234m}Pa, and ^{234}U are assumed to be in radioactive equilibrium with ^{238}U in all organs and tissues.

Table 10

Average activity concentrations in tissues and annual absorbed doses resulting from internal irradiation by thorium-230

Organ or tissue	Activity concentration (mBq kg^{-1})	Annual absorbed doses (10^{-7} Gy) α
Gonads	0.3	0.07
Breast	0.3	0.07
Lungs	20	4.7
Cortical bone	20	
Trabecular bone	70	
Red bone marrow	0.3	5.6
Bone lining cells		74
Thyroid	0.3	0.07
Kidneys	10	2.4
Other tissues	0.3	0.07

Table 11

Average activity concentrations in tissues and annual absorbed doses resulting from internal irradiation by radium-226 and its short-lived decay products [a/]

Organ or tissue	Activity concentration (mBq kg^{-1})		Annual absorbed doses (10^{-7} Gy)					
	^{226}Ra	^{222}Rn [b/]	^{226}Ra α	^{222}Rn α	^{218}Po α	^{214}Pb β,γ	^{214}Bi β,γ	^{214}Po α
Gonads	2.7	0.9	0.7	0.3	0.3	0.01	0.03	0.4
Breast	2.7	0.9	0.7	0.3	0.3	0.01	0.03	0.4
Lungs	2.7	0.9	0.7	0.3	0.3	0.01	0.03	0.4
Cortical bone	170	60						
Trabecular bone	170	60						
Red bone marrow	2.7	0.9	2.0	0.8	0.9	0.2	0.6	1.1
Bone lining cells			22	9.1	9.9	0.7	1.7	13
Thyroid	2.7	0.9	0.7	0.3	0.3	0.01	0.03	0.4
Other tissues	2.7	0.9	0.7	0.3	0.3	0.01	0.03	0.4

a/ Includes doses resulting from the formation of radon-222 and its short-lived decay products in the body by decay of radium-226 but does not take into account the doses arising from inhalation of radon-222 and its daughters.

b/ ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po are assumed to be in radioactive equilibrium with radon-222 in all organs and tissues.

Table 12

Estimated equilibrium equivalent concentration of radon-222 and annual effective dose equivalents arising from inhalation

		Populations in temperate regions	Global population
OUTDOOR EXPOSURE			
Equilibrium equivalent concentration	(Bq m^{-3})	1.8	1.8
Range of mean annual values	(Bq m^{-3})	0.1-10	0.1-10
Average annual effective dose equivalent	(mSv)	0.06	0.06
Range of mean annual values	(mSv)	0.003-0.3	0.003-0.06
INDOOR EXPOSURE			
Equilibrium equivalent concentration	(Bq m^{-3})	15	
Range of mean values in various countries	(Bq m^{-3})	5-60	
Average annual effective dose equivalent	(mSv)	0.92	0.7
Range of mean values in various countries	(mSv)	0.3-3.7	
Total average annual effective dose equivalent	(mSv)	1.0	0.8

Table 13

Estimated average activity concentrations of ^{210}Pb, ^{210}Bi, and ^{210}Po in tissues of non-smokers in areas of normal dietary intake, and corresponding annual absorbed doses

Organ or tissue	Lead-210		Bismuth-210		Polonium-210	
	Activity concentration ($Bq\ kg^{-1}$)	Annual absorbed dose (μGy) β	Activity concentration ($Bq\ kg^{-1}$)	Annual absorbed dose (μGy) β	Activity concentration ($Bq\ kg^{-1}$)	Annual absorbed dose (μGy) α
Gonads	0.2	0.04	0.2	0.4	0.2	5.4
Breast	0.2	0.04	0.2	0.4	0.2	5.4
Lungs	0.2	0.04	0.2	0.4	0.1	2.7
Cortical bone	3		3		2.4	
Trabecular bone	3		3		2.4	
Red bone marrow	0.14	0.17	0.14	1.7	0.11	5.1
Bone lining cells		0.44		4.2		36
Thyroid	0.2	0.04	0.2	0.4	0.2	5.4
Other tissues	0.2	0.04	0.2	0.4	0.2	5.4
Annual effective dose equivalent (μSv)		0.07		0.7		130

Table 14

Average activity concentrations in tissues and annual absorbed doses resulting from internal irradiation by thorium-232

Organ or tissue	Activity concentration ($mBq\ kg^{-1}$)	Annual absorbed doses (10^{-7} Gy) α
Gonads	0.15	0.03
Breast	0.15	0.03
Lungs	20	4.0
Cortical bone	6	
Trabecular bone	24	
Red bone marrow	0.15	1.7
Bone lining cells		20
Thyroid	0.15	0.03
Kidneys	3	0.6
Liver	2	0.4
Other tissues	0.15	0.03

Table 15

Average activity concentrations in tissues and annual absorbed doses resulting from internal irradiation by radium-228 and its decay products [a/]

Organ or tissue	Activity concentration (mBq kg^{-1})		Annual absorbed doses (10^{-8} Gy)									
			^{228}Ra	^{228}Ac	^{228}Th	^{224}Ra	^{220}Rn	^{216}Po	^{212}Pb	^{212}Bi	^{212}Po	^{208}Tl
	^{228}Ra[b/]/^{228}Th[c/]		β	β,γ	α	α	α	α	β,γ	α,β,γ	α	β,γ
Gonads	4	0.5	0.03	1.1	1.4	1.4	1.6	1.7	0.05	0.5	1.4	0.07
Breast	4	0.5	0.03	1.1	1.4	1.4	1.6	1.7	0.05	0.5	1.4	0.07
Lungs	4	15	0.03	1.1	41	43	48	51	1.4	16	43	2.0
Cortical bone	50	50										
Trabecular bone	50	50										
Red bone marrow	4	0.5	0.14	4.1	5.9	6.2	6.9	7.4	1.1	2.3	6.2	1.6
Bone lining cells			0.30	10	74	78	87	93	3.4	29	77	5.5
Thyroid	4	0.5	0.03	1.1	1.4	1.4	1.6	1.7	0.05	0.5	1.4	0.07
Kidneys	4	10	0.03	1.1	27	29	32	34	0.9	11	28	1.3
Liver	4	5	0.03	1.1	14	14	16	17	0.5	5.4	14	0.7
Other tissue	4	0.5	0.03	1.1	1.4	1.4	1.6	1.7	0.05	0.5	1.4	0.07

a/ Includes doses resulting from the formation of radon-220 and its decay products in the body by decay of radium-224 but does not take into account the doses arising from inhalation of radon-220 and its daughters.

b/ Actinium-228 is assumed to be in radioactive equilibrium with radium-228.

c/ ^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Pb, and ^{212}Bi are assumed to be in radioactive equilibrium with thorium-228; owing to the decay characteristics of bismuth-212, the activity concentrations of polonium-212 and of thallium-208 are 64 % and 36 % of those of bismuth-212, respectively.

Table 16

Estimated equilibrium equivalent concentration of radon-220 and annual effective dose equivalents arising from inhalation

		Populations in temperate regions	Global population
OUTDOOR EXPOSURE			
Equilibrium equivalent concentration	(Bq m^{-3})	0.2	0.2
Annual effective dose equivalent	(mSv)	0.02	0.02
INDOOR EXPOSURE			
Equilibrium equivalent concentration	(Bq m^{-3})	0.7	
Annual effective dose equivalent	(mSv)	0.20	0.15
Total annual effective dose equivalent	(mSv)	0.22	0.17

Table 17

Estimated per caput annual effective dose equivalents from natural sources in areas of normal background

Source of irradiation	Annual effective dose equivalent (μSv)		
	External irradiation	Internal irradiation	Total
COSMIC RAYS			
- Ionizing component	280		280
- Neutron component	21		21
COSMOGENIC RADIONUCLIDES		15	15
PRIMORDIAL RADIONUCLIDES			
^{40}K	120	180	300
^{87}Rb		6	6
^{238}U series			
$^{238}U \rightarrow ^{234}U$		10	
^{230}Th		7	
^{226}Ra	90	7	1044
$^{222}Rn \rightarrow ^{214}Po$		800	
$^{210}Pb \rightarrow ^{210}Po$		130	
^{232}Th series			
^{232}Th		3	
$^{228}Ra \rightarrow ^{224}Ra$	140	13	326
$^{220}Rn \rightarrow ^{208}Tl$		170	
TOTAL (rounded)	650	1340	2000

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