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NOTE

Throughout the present report and the annexes thereto, references to the annexes are indicated by a letter followed by a number: the letter denotes the relevant annex and the number the paragraph therein. Within each annex, references to its scientific bibliography are indicated by numbers.

Symbols of United Nations documents are composed of capital letters combined with figures. Mention of such a symbol indicates a reference to a United Nations document.

ANNEX E

RADIATION FROM NATURAL SOURCES

CONTENTS

Introduction

1. The radiation from natural sources at any specific location remains relatively constant with time; it does, however, vary from place to place. Natural radiation arises from two sources—cosmic rays and naturally occurring radio-active materials. While cosmic rays are predominantly an external source of irradiation, naturally occurring radio-active materials give rise to both external and internal irradiation of the human body. A distinguishing characteristic of irradiation by natural sources is that the entire world population has been exposed to it since the beginning of time and will continue to be exposed to it in the future.

2. The biological effect of ionizing radiation varies with the type of radiation, and, in order to take this into account, a weighting factor is used to obtain the tissue dose in rem from the corresponding absorbed dose in rad. This factor is known as the relative biological effectiveness (RBE) and the usual definition is given in annex A. However, the RBE factor for a particular type of radiation is not a constant, and varies with a number of other parameters such as dose-rate, dose fractionation, type of biological effect, oxygen tension and temperature.

3. The RBE values given in annex A are those proposed for radiation protection purposes[1,2] and are generally thought to be rather conservative, particularly in the case of α-particles and neutrons. For the estimation of biological damage it is quite probable that lower values are more applicable. For instance, the 1959 ICRP Committee II report[3] states the following with regard to the RBE for α-particles:

> "Many experiments[4] indicate that (RBE) α is much smaller than 10 for biological damage resulting from acute exposure—perhaps as small as 1.4—but for chronic exposures, much higher applicable values have been reported.[5] Therefore, until more data for chronic exposures are available, it would be unwise to use a value of (RBE) $\alpha < 10$."

For low energy electrons of ≤ 0.03 MeV, Shtukkenberg[6] suggests that the RBE is 2.8-3.0 (i.e., greater than the usual value of 1.7), when one takes into account the smaller biological effect produced by chronic irradiation when compared to a single exposure. In the light of all the uncertainties, it is thought prudent to use the RBE values given in annex A in order to estimate the exposure pattern in man, but to keep in mind that in general these values will be too high (see also annex H). Where possible in the present annex, tissue doses will be given in rem as well as in rad.

I. Cosmic rays

Nature of radiation

4. Primary cosmic radiation may be divided into three categories: galactic cosmic radiation, geomagnetically trapped radiation, and solar cosmic radiation.

(*a*) Galactic cosmic radiation presents a more or less constant space environmental factor, and its particle composition has been quite well determined. Outside the atmosphere at latitudes above 55°, primary cosmic rays of galactic origin consist of 87 per cent protons, 12 per cent alpha particles, and 1 per cent heavier nuclei (C, N, O, Mg, Ca, Fe).[7-10]

(*b*) Geomagnetically trapped radiation is the second category. At higher altitudes, in regions symmetrical with regard to the magnetic equator, there exist two radiation belts containing electrons and protons which have been captured by the magnetic field of the earth.[11-14] The inner belt begins at about 1,000 km altitude, reaches a maximum intensity at about 3,000 km and extends from 30° N to 30° S. The outer belt begins at an altitude of about 12,000 km, passes through a maximum intensity at about 15,000 km and extends from 60° N to 60° S. The energy spectrum of the particles in each belt differs considerably but has not been investigated fully enough to give an accurate estimate of the radiation dose-rate in these regions. The dose-rates will be dependent on the amount of shielding assumed and, for the inner radiation belt, values of 10 and 120 rad per hour have been suggested[15,16] for 1 and 2 g per cm^2 shielding respectively. Dose rates in the outer belt may be of the order of 10^4 rad per hour[17] owing to soft electron bremsstrahlung, but this can be reduced considerably by shielding. A further high intensity field of low energy electrons[18,19] is to be found at high latitudes ($> 60°$) and altitudes (> 25 km) and is associated with auroral processes.

(*c*) Solar cosmic radiation is the third major radiation phenomenon. Large fluxes of protons are observed to reach the vicinity of the earth following severe solar flares which occur on the surface of the sun. Because of the potential danger of space travel and because of the relationships to solar physics, magnetic fields, and many geophysical events, this radiation is under intense study. Solar cosmic ray events may be divided into two classes: "high energy" and "low energy". During high energy events a significant number of particles have energies high enough to produce effects observable by ground level neutron monitors, whereas high altitude measurements or riometer measurements are necessary to detect the low energy events. The high energy events appear to be much less frequent than those of low energy. Only five such events were detected during the twenty years preceding 1959; however, an additional five events have been detected during 1959 and 1960, three of which occurred in one month, November 1960. The low energy events, on the other hand, have been observed to occur at the rate of ten per year since 1957. The most intense high-energy outburst of solar protons recorded to date was observed following the great solar flare of 23 February 1956. Shortly after the beginning of the flare, solar particles with energies of several Bev began striking the ionosphere. Data available from a number of flare events seem to indicate that the initial flux reaching the vicinity of the earth may be monodirectional with the flux, then becoming isotropic after about the first hour. There is also some evidence that the spectrum of the initial particles may be considerably harder than that of those arriving later. Measurements made with the Pioneer V space probe have been somewhat enlightening on the behavior of solar protons in free space. The probe encountered outbursts of solar protons at a distance of about 5 million km from the earth during the period from 27 March to 6 April 1960. Unlike the radiation belts, the solar particles are not restricted to a small region of space that could be avoided or traversed rapidly, but would apparently be encountered throughout the solar system. Consequently, steps will have to be taken to shield directly against these particles in order to achieve manned missions of any appreciable time duration.

5. The primary particles interact with nuclei of the upper atmosphere, producing secondary radiation, which consists of mesons, electrons, photons, protons and neutrons—all with a very wide range of energies. Electrons and photons constitute the soft component of the secondary radiation, protons and neutrons the nucleonic component. The primary radiation intensity gradually decreases with decrease in altitude and at about 20 km it has practically disappeared, so that below this altitude cosmic radiation is almost entirely secondary in nature. In the altitude region above 20 km, the proportion of secondary radiation rapidly decreases until, at about 50 km, the radiation dose-rate is due predominantly to the primary component, except in the case of the auroral regions and the inner and outer radiation belts (para. 4). The increase in cosmic radiation dose-rate with altitude is such that above about 2 km, cosmic radiation becomes the major dose-rate contributor in man.

Radiation dose-rates

6. The radiation dose-rate due to the ionizing component of cosmic rays is generally estimated by measuring the number of ion pairs per cm^3/sec, using an energy independent ionization chamber, and then converting this value to the rate of absorption of energy assuming that 34 eV are required to form 1 ion pair. Many measurements of this type have been made. These measurements, however, do not take into account the radiation dose-rate due to the neutron component of cosmic rays, and this must be measured separately. Many measurements of cosmic ray neutron flux have been made but there are relatively few estimates of the resulting tissue dose-rate. This is due to the fact that the tissue dose-rate is very dependent on the neutron energy spectrum[20] which is extremely difficult to determine. The cosmic radiation dose-rate often used as a "base level" is that at sea level for high altitudes ($\sim 70°$). There are indications[21,22] that the most reliable figure for the ionizing component in this region is 1.90-1.96 ion-pairs per cm^3/sec, which gives a soft tissue and gonad dose-rate of about 28 mrad/y.

7. The cosmic ray neutron component results in a tissue dose-rate which, at sea level for middle latitudes, has been estimated by Patterson *et al.*[23] using three different type neutron detectors, which could respond to different ranges of neutron energy. Patterson's calculations show that the dose-rate from the neutron component of cosmic rays at sea levels is 25 mrem/y. This estimate is the dose-rate at the skin using the values of RBE established by the United States National Committee on Radiation Protection and Measures and ignores the absorption of neutrons in building structures and the body itself. It has been assumed that there is an average of 10 cm of building materials in roofing materials, timbers and ceilings, and that the average depth of the gonads and bone-marrow is 4 cm. By applying corrections for the

absorption of the various energies of neutrons, assuming these materials to be tissue equivalent, and assuming that the average time spent out of doors is seven hours a day, the resultant tissue dose-rate is 13 mrem/y. (These data are based on the depth dose curves for neutrons given in reference 24.) This is probably more reliable than the value of 18 mrem/y for sea level at 51° N given by Tobias[19] whose estimate was based on measurements using a single type neutron detector which did not give a direct measurement of fast neutron flux, the most critical portion of the neutron energy spectrum with regard to dose-rate considerations. According to Shtukkenberg's[25] calculations, the cosmic radiation fast neutron (> 10 MeV) tissue dose-rate at sea level is approximately 10 per cent of the total dose-rate. He suggests that the total dose-rate resulting from cosmic radiation is 88 mrem/y, if an RBE value of 10 is assumed for densely ionizing particles with energies up to 15 MeV, and 57 mrem/y, if a value of 6.5 is used.

8. It is therefore suggested that 50 mrem per year be taken as a typical value for the total cosmic radiation tissue dose-rate for sea level at middle latitudes. The value is subject to variations with a number of parameters, as discussed in paragraphs 9-18 below.

Variations with latitude and longitude

9. Cosmic ray intensity exhibits a latitude effect which is due to the earth's magnetic field preventing the incoming primary particles below a certain critical minimum energy from reaching the earth's atmosphere. This critical cut-off energy decreases with increasing latitude, the net result being that the cosmic ray intensity at the geomagnetic equator is lower than at other latitudes. The intensity remains relatively constant between 15° N and 15° S, then shows a rapid increase until about 50° latitude, after which it remains practically constant again. The latitude effect is generally expressed as the percentage increase at 50° over the intensity at the equator.

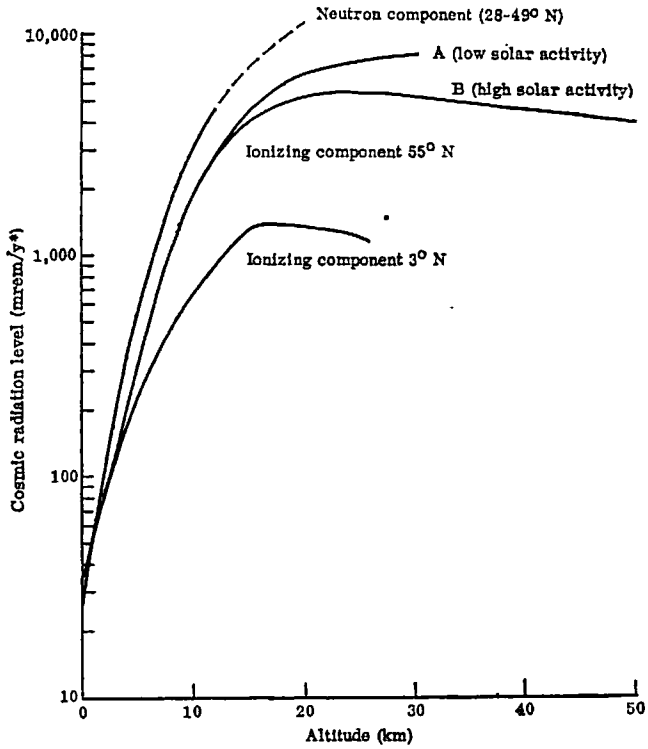
10. The average value[26] for the latitude effect of the ionizing component of cosmic radiation at sea level is 10 per cent. The percentage increases slowly to a value of about 30 per cent at an altitude of 5 km and then much more quickly to a value of about 350 per cent at the transition region (about 20 km) of the atmosphere (para. 15).

11. Since the neutron component of cosmic radiation includes neutrons produced by interaction with the atmosphere, it also exhibits a large latitude effect.[27] At altitudes from sea level up to about 3 km, the latitude effect is about 150 per cent and at 9 km, is about 250 per cent.

12. Changes in cosmic ray intensity with longitude are expected to occur[28] since the magnetic centre of the earth and the geometrical centre do not coincide, the magnetic centre of the earth being approximately 300 km from the centre of the earth along a line passing approximately through 10° N geomagnetic latitude and 160° E longitude. The intensity of the ionizing component at sea level has been found to vary about 5 per cent along the geomagnetic equator,[29] the effect diminishing at higher latitudes.[30] The nucleon intensity shows similar but larger intensity variations with change in longitude.[27, 31]

Variations with altitude

13. The variation in composition of the cosmic radiation with altitudes up to 50 km has been described in paragraph 4. Figure 1 gives the measured variation of cosmic radiation dose-rates in mrem per year with altitude for the ionizing component[32] at 3° N and 55° N, and for the neutron component[23] in the latitude range 28-49° N. The significance of curves A and B is explained in paragraph 15.



* See annex A for comment on RBE values used.

Figure 1. Variation of cosmic radiation level with altitude

14. Typical values for the total cosmic radiation tissue dose-rates for various altitudes at the equator, 30° and 50° latitude, have been estimated, assuming that Patterson's[23] results for the neutron component at various altitudes apply to a latitude of 50° and that the latitude variations are as suggested in paragraphs 10-11 (table I).

Variations with time

15. Time variations of cosmic ray intensity result from a number of causes including solar flares, the 11-year solar cycle, the 27-day lunar period, temperature changes in the upper layers of the atmosphere, barometric pressure changes and air fronts. The modification in cosmic ray intensity which is associated with the 11-year cycle[33] of solar activity is most pronounced for the lower part of the energy spectrum of the primary cosmic radiation and is therefore only evident at high altitudes where it results in a minimum intensity at the period of maximum solar activity. This is illustrated by curves A and B in figure 1 which show[32] the total ionization as a function of altitude in 1954 (curve A) when the sun was at its lowest ebb in twenty-two years, and in 1937 (curve B), a year of high solar activity.

16. Further variations associated with the sun are the so-called cosmic ray storms which are of short duration, one day up to a couple of weeks. They start with a sudden decrease, or series of decreases, in cosmic ray intensity and are followed by a slow recovery. These storms and decreases in intensity are correlated with the

number and size of sun spot groups as well as the appearance of solar particles.[34] Therefore they also follow the 11-year solar cycle.

17. The sun also acts as a powerful source of cosmic radiation during prominent flares. The spectrum of protons produced by these flares is much more enhanced in the low energy portion than that for the primary cosmic radiation[32] and in most cases moderate amounts of shielding will be effective. The largest flares, for example the giant flares of 4 May 1960 and of 23 February 1956, may, however, produce dose-rates which are quite high at altitudes of the order of 10-20 km and their effect is considerable even at sea level. Calculations for the February 1956 increase show[35] that the integrated exposure over the duration of the increase was 5 to 10 rad at an altitude of 15 km. Solar particles produce a strong influx at high latitudes of protons having energies from a few tens to many hundreds of MeV. As these protons continue to bombard the earth's atmosphere for days they may represent a major radiation problem in the stratosphere especially as they may produce dose-rates of the order of 10 rem/hr at 20-25 km altitude.[36] During years of high solar activity a dozen or more such events may occur per year.

18. The neutron intensity would also be expected to exhibit a dependence on solar activity corresponding to the solar modification of primary cosmic radiation. Short-term variations at high altitudes and latitudes and associated with periods of high sunspot activity have also been observed. For instance, Simpson[27] reports increases in intensity of at least 30 per cent at 9 km altitude which persist for the order of days. Further variation in the neutron component will also occur near the earth's surface due to alterations in the moisture content of the soil, and it is also affected by the moisture content of dense cloud formations.[37]

II. Natural radio-activity in the earth's crust

Naturally occurring radio-active nuclides

19. Naturally occurring radio-active materials are widely distributed throughout the earth's crust and the resulting gamma ray dose to mankind varies from a value somewhat less than that due to cosmic rays to values many times higher. Some of the more important of these nuclides are the long-lived U^{238}, Th^{232} and Ra^{226} (and their shorter-lived daughter products), K^{40} and the cosmic ray produced isotopes C^{14} and H^3. Other isotopes such as Rb^{87}, La^{138}, Sm^{147} and Lu^{176} also exist in nature but their abundance is so low as to make a negligible contribution to the dose received by mankind. The physical characteristics of some of these isotopes are given in table II.

Concentration in common rocks

20. In general, natural radio-nuclides are found to be more concentrated in granitic rocks than in basaltic rocks.[38,39] Limestones and sandstones are low in radio-activity, but certain shales are more radio-active, especially those containing organic matter.[40] Marine sediments appear to be more radio-active than either non-marine or estuarian deposits.[38]

Uranium and thorium

21. Uranium ore has been found in large quantities in Australia, Canada, Czechoslovakia, Republic of the Congo (Leopoldville), South Africa, the United States, the Soviet Union and other areas. Large deposits of monazite, the principal thorium-bearing mineral, are found in Brazil, the United Arab Republic, China, India and the United States. Although thorium is more abundant than uranium, uranium is found in a much greater variety of chemical combinations. Table III shows their concentration in various rocks, as determined by a number of workers, expressed as $\mu\mu c/g$.

Radium-226

22. Ra^{226} is one of the daughter products of U^{238} but, because of leaching and weathering, it is not necessarily in equilibrium in soil with its long-lived parent. There is a considerable range of concentration in various rocks, as indicated by table III. Particularly high concentrations are found in alum shales in Sweden.[41,42] The Ra^{226} concentration in the soil in various parts of the United States has been found by measurement to vary between 0.09 and 0.8 $\mu\mu c/g$ soil.[26]

Potassium

23. Potassium is relatively abundant in nature. Its radio-active isotope K^{40} constitutes 0.0118 per cent[43] of the total amount of potassium and contributes[44] 28 β-dps per g K and 3.45 γ-dps per g K. The K^{40} content of various rocks is given in table III. It has been estimated that the potassium content of soil is about 10^{-3} to 3×10^{-2} g K/g soil[45] (1 to 30 $\mu\mu c K^{40}/g$ soil.)

Rn^{222} and Rn^{220} in the earth's crust

24. Since uranium and thorium are almost universally distributed, their respective short-lived gaseous daughter products, Rn^{222} and Rn^{220}, accumulate in soil and rocks. The daughter products of this trapped Rn^{222} and Rn^{220} contribute over half the observed gamma activity of uranium minerals.[41] The Rn^{222} and Rn^{220} in the soil diffuse into the air at a quite variable rate, depending on a number of factors including moisture content of the ground,[46] presence of snow,[47] amount of rainfall,[48,49] conditions in soil and atmosphere, particularly atmospheric turbulence and pressure.

Dose-rates from the earth's crust

25. The gamma dose-rates in air over radio-active rocks and soils can be calculated from the energies, absorption factors and relative abundances of the various component gamma rays, allowance being made for scattered radiation. The expressions obtained by Hultqvist[42] and O'Brien *et al.*[50] for the gamma dose-rates in air above ground containing uniform concentrations of U^{238}, Th^{232} and K^{40} agree to within 10 per cent. The average of their expressions gives the following relations between the dose-rate in air (D, mrad/y) at a height of one metre above ground containing uniform concentrations (S, $\mu\mu c/g$) of U^{238}, Th^{232} (both in equilibrium with their daughters) and K^{40}:

$$\left.\begin{aligned} D_U &= 17.8 \times S_U \\ D_{Th} &= 25.5 \times S_{Th} \\ D_K &= 1.56 \times S_K \end{aligned}\right\} \qquad (1)$$

26. The β-particle emission of these naturally-occurring radio-nuclides can contribute an external dose to the human skin. These skin dose-rates have been calculated by O'Brien *et al.*[50] for β-emission from U^{238}, Th^{232} and K^{40} in soil assuming homogenous distribution and complete equilibrium between the U^{238} and Th^{232} and their decay products. The external contribution to the dose-rate delivered to susceptible organs (such as

gonads, bone, etc.) resulting from β-emission, must be regarded as negligible.

27. Typical estimates of the average dose-rates in air at a height of one metre above limestone may be of the order of 20 mrad/y and that for granite areas may be of the order of 150 mrad/y. It is obvious, however, that there will be quite large variations in these values, and this is borne out by the measured terrestrial dose-rates in air reported for areas in various countries as given in table IV. Further, much higher values are reported for some areas, e.g., monazite sands, where the uranium and thorium contents are very high (see section VII below).

28. The terrestrial gamma dose-rate inside buildings will, generally, be different from the value out of doors owing to the different radio-active content of the building materials and also the attenuation effect of the walls for the radiation from sources outside the building. A further small increase in dose-rate may be produced by the accumulation of Rn^{222} and Rn^{220} as a result of poor ventilation in the buildings (see section IV below). Reported terrestrial dose-rates in air inside buildings in various countries are given in table V.

29. In order to obtain tissue dose-rates to specific organs due to external gamma sources, allowance must be made for attenuation by intervening portions of the body. O'Brien *et al.*[50] have calculated the dose-rates in man at various depths as fractions of the free-air gamma dose-rates. Assuming that the testicles, ovaries and bone-marrow are at depths[51] of 1, 7 and 4 cm, the resulting screening factors are 0.68, 0.58 and 0.62, respectively. These are in very good agreement with the average experimentally determined screening factors obtained by Spiers[52] using a water-filled model—0.70, 0.56 and 0.64 respectively. It is, therefore, suggested that a value of 0.6 be used as the screening factor for gonads and bone-marrow in the case of terrestrial radiation. (F III, 18)

30. The estimation of mean dose-rate to a population should be made by a carefully planned series of measurements of dose-rates both indoors and out of doors and then weighting the measurements according to time spent in each place. A very good example of such a survey is one which was recently made in four areas in the United Kingdom.[53] The mean values of local gamma-radiation dose-rates obtained are given in table VI. In computing the mean dose-rates to the gonads and bone marrow, screening factors of 0.63 and 0.64 respectively were used and it was assumed than an average of six hours per day per person was spent out of doors.

31. Insufficient measurements have been made to enable a reliable estimate of the mean dose-rate to the world population to be made. It should be pointed out that the major part of most people's lives in most areas of the world is spent inside buildings. With this in mind, consideration of tables IV and V seems to indicate that, except for certain regions of high activity, the average terrestrial gamma dose-rate in air is of the order of 80 mrad/y, i.e., a mean gonad and bone dose-rate to the world population from terrestrial gamma radiation is only about 50 mrad/y (para. 29).

III. Natural radio-activity in water

32. An extremely wide range of natural radio-activities exists in various types of water, depending largely upon their origin. The levels of natural activity originating from uranium and thorium series are found to be high in certain natural springs which are found in areas where there are high concentrations of uranium and thorium in the soil. Similarly, drinking water exhibits wide variations of activity depending upon its origin and on the treatment it receives before it becomes available for consumption. High levels of natural potassium-40 activities are found in sea-water.

Public water supplies

33. Public water supplies are of interest since drinking water is one of the modes of entrance of natural radio-activity into the body. Table VII gives concentrations of Ra^{226} and Rn^{222} present in various public water supplies. It should be pointed out that the radium content of water is reduced by the introduction of filtration and/or softener systems, so that the intake of radium from a particular supply may be modified in the case of some individuals by the use of domestic water softeners. Lucas[54] quotes a case where one of these units (ion-exchange type) removed 98 per cent of the Ra^{226} present in the normal water supply.

34. Many drinking water supplies will also contain naturally occurring Th^{232} and/or its decay products. Krause[55] has investigated the Ra^{228} content of twenty-six samples of well-water from the Illinois (United States) sandstone area and has compared them with the Ra^{226} contents of the same samples which had been previously measured by Lucas.[56] The Ra^{228}/Ra^{226} ratio covered an extremely wide range of values, 0.04 to 2.43, with an average of 0.60. The Ra^{228} concentrations ranged from 0.9 to 7.9 $\mu\mu c/l$, whilst Ra^{226} went from 3 to 36 $\mu\mu c/l$.

Ocean water, rivers and natural springs

35. Typical concentration of U^{238}, Th^{232}, Ra^{226} and K^{40} in sea-water are respectively 0.2-9 $\mu\mu c/l$,[57] 0.1—1.10^{-3} $\mu\mu c/l$,[58] 0.02—0.3 $\mu\mu c/l$[59] and 300 $\mu\mu c/l$.[60] Table VIII gives the concentrations of U^{238}, Ra^{226} and Rn^{222} present in various natural waters and springs. Spring-waters may exhibit extremely high radio-active concentrations, particularly of Rn^{222}, but as they are consumed regularly only by a very small percentage of populations, and since Rn^{222} ingested from drinking water probably has a mean life of about one hour in the body,[61] the resulting mean dose to the world population from spring-water is negligible.

Skeletal Ra^{226} content due to drinking water

36. The skeletal content of Ra^{226} is determined by its introduction into the body through food, water and, to a lesser extent, air. Muth *et al.*[62] have shown that under normal environmental conditions only about 10 per cent of the Ra^{226} enters the human body through water and about 90 per cent from food. When the Ra^{226} concentration in water is relatively high and the intake from water exceeds the intake from food, some correlation is found to exist between the skeletal concentration and the concentration in water.[54] With relatively low (normal) Ra^{226} concentrations in water, no such correlation is observed as the skeletal Ra^{226} content is then basically determined by its intake from food.

IV. Natural radio-activity in the lower atmosphere

Rn^{222} and Rn^{220} and their decay products

37. Wherever there are uranium or thorium bearing minerals present in the soil, the gaseous decay products

Rn^{222} and Rn^{220} are injected into the atmosphere by diffusion (para. 24). The rate of injection varies considerably with seasonal and meteorological conditions. Measurements of Rn^{222} and Rn^{220} and/or their daughter product activities is often carried out by a combination of filtration and ionization chamber or scintillation methods.[63] The daughter products, in the form of ionized atoms, attach themselves to the aerosols and dust particles which are always present in the air. The collection efficiency of filter papers for these particles is often very uncertain and depends on the linear air velocity through the paper and the size range of the dust particles in the air.[64,65] Thus, in low dust atmospheres such as those of air-conditioned rooms, the retention of the daughter products by filter papers may be very low. Ion collection efficiency may, however, approach 100 per cent by the application of a suitable electric field.[66] In addition, the Rn^{222} and Rn^{220} present in the atmosphere are not necessarily in equilibrium with their daughter products and will also contain varying fractions of uncombined atoms of daughter products, both of which affect the dose-rate to the lungs upon inhalation (para. 42). The concentration of Rn^{222} and Rn^{220} will also vary with height, for instance the average value at a height of 10 m for Rn^{222} is 90 per cent of that at ground level.[25,67,68] Rn^{220}, by virtue of its very short half-life, will virtually have disappeared at heights of 10-20 m. The average concentrations of Rn^{222} and Rn^{220} present in free air at ground level in various regions are given in table IX. Values are particularly dependent upon the length of time the air mass spends over continental land masses.[67,69,70] Also, in areas of high radio-activity and under special meteorological conditions, e.g. smog and temperature inversion, values may be higher by several factors of ten.

38. As the majority of the people spend a large part of their time in buildings, the average natural radioactivity concentration in air which refers to the world population is more dependent upon the level in buildings than in free air. In general, the level indoors is higher than that out of doors and it is dependent upon the building construction materials and the ventilation conditions. The level out of doors will determine the concentration that will be reached by very efficient ventilation of the building. The results of measurement by Hultqvist[42] in three types of buildings in Sweden for conditions with and without ventilation are given in table X. A ventilation rate of 10^{-3}/sec was used, i.e., the air in the building was renewed every seventeen minutes.

39. Reported Rn^{222} content of the air indoors at various localities is given in table XI. Consideration of these data indicates that the best estimate of a "world average" concentration of Rn^{222} in air may be of the order of 0.5 $\mu\mu$c/l. The corresponding figure for Rn^{220} may be of the order of 0.02 $\mu\mu$c/l.

40. The external gamma dose-rate in air (D) produced by a concentration of C $\mu\mu$c/l of Rn^{222} or Rn^{220} in equilibrium with their decay products per litre of air can be calculated by Hultqvist's relation:[42]

$$D = 14C \text{ mrad/y}$$

In obtaining the dose to various body organs allowance must be made for body shielding. The screening factor of 0.6 used previously for terrestrial radiation (para. 29) will again be used here. Hence, for "average" air concentrations of Rn^{222} and Rn^{220} (para. 39), the total body tissue dose-rate will be of the order of 4.5 mrem/y. It should be pointed out, however, that this contribution to the tissue dose-rates will have been included in any measurement of local gamma-radiation dose-rates that have been made and so is allowed for in the average local gamma dose-rate given in paragraph 31.

41. There will also be a further total body tissue dose produced by the Rn^{222} and Rn^{220} in the air resulting from that portion which is transferred via the blood from contact with the alveolar air. Using Spiers[53] results, the total dose-rate to soft tissues due to the inhalation of air containing 0.5 $\mu\mu$c/l of Rn^{222} in equilibrium with its daughter products, is of the order of 3 mrem per year. Ruzer's results[71] indicate that the whole body dose-rate due to the inhalation of 0.5 $\mu\mu$c/l of Rn^{222} is of the order of 0.01 mrem per year.

42. The dose-rate to the lungs from Rn^{222} and Rn^{220} and their decay products occurs as a result of deposition and/or passage back and forth through the tracheobronchial tree of these decay products[72] and depends largely on their size, specific activity and percentage of uncombined atoms,[73] since these determine the amount of radio-activity retained in the lungs. Rn^{222} and Rn^{220}, being gases, are retained only to a very small extent, and so do not make a very large contributon to the dose-rate. Stannard[74] gives the mass deposition of small particles in the respiratory tract (figure 2), derived from the results given by Hultqvist.[42] Values for dose-rates to the lung for exposure to Rn^{222} or Rn^{220} in equilibrium have been calculated by various workers. For instance, using the expressions of Hultqvist,[42] Morgan,[42] Ruzer,[71] Shapiro,[75] and Schraub,[76] values are obtained of 20 mrad (200 mrem), 90 mrad (900 mrem), 10 mrad (100 mrem), 10 mrad (100 mrem), 250 mrem, respectively, for the annual dose to the lungs from a continuous concentration of 0.5 $\mu\mu$c/l Rn^{222} in equilibrium. The variations in these estimates are chiefly due to the differences in the assumption regarding time spent in the relevant locale, respiration velocity and the weight of the irradiated lung tissue. Hultqvist[42] has estimated the dose-rate

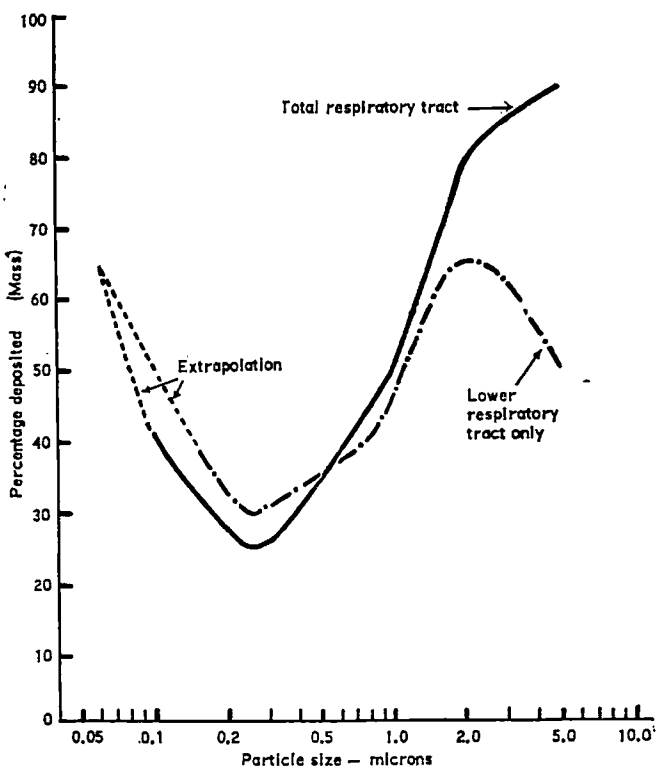


Figure 2. Percentage mass deposition of small particles in the respiratory tract

to the lungs from Rn^{222} and its decay products and from Rn^{220} and its decay products in the case of radio-active equilibrium and also where this equilibrium has been greatly disturbed by a high ventilation rate (10^{-3}/sec.). The dose-rates to the lungs along with the average concentrations of Rn^{222} and Rn^{220} in air for three types of buildings in Sweden are given in table X. It is apparent that the lungs receive a higher irradiation from natural sources than any other body tissue.

Pb^{210}, Bi^{210m} and Po^{210}

43. The daughter products, Po^{218}, Pb^{214}, Bi^{214} and Po^{214}, because of their short half-lives, are normally not very far from secular equilibrium with the parent Rn^{222}, but the concentrations of Pb^{210}, Bi^{210m} and Po^{210} will be relatively much lower at ground level than their equilibrium values, as they will be washed out of the atmosphere long before equilibrium has been reached. Measured levels of Pb^{210}, Bi^{210m} and Po^{210} in the air at ground level are given in table XII. These concentrations are insignificant with respect to dose considerations.

Carbon-14*

44. Carbon is one of the elements that are essential to all forms of life and thus is involved in most biological and geochemical processes on the earth. Associated with the stable isotopes of carbon (C^{12} and about 1.1 per cent C^{13}), there is always a very small but variable amount of C^{14}, a pure β-emitting (E_{max} = 0.165 MeV) radio-active isotope of carbon with a half-life of 5760 ± 50 years.[77]

45. C^{14} is formed upon absorption of neutrons in the nitrogen nuclei of the atmosphere. When the neutrons involved are of cosmic ray origin, the C^{14} formed is referred to as "natural", and when the neutrons originate from nuclear testing, the resulting C^{14} is "artificial".

46. Due to isotopic fractionation in most processes in which carbon is involved, small variations occur in the relative amounts of the three isotopes of carbon found in nature. Thus, for example, the C^{13}/C^{12} ratio in plant material is 1.7 per cent less than that in the atmosphere[78,79] and the change for the C^{14}/C^{12} ratio is twice this amount.[80,81]

Production of natural C^{14}

47. The C^{14} produced in the atmosphere owing to absorption of cosmic ray neutrons may be estimated from flux-energy data and the neutron cross-sections of the various constituents of the atmosphere. These cosmic ray neutrons are entirely secondary in nature.

48. The neutrons are slowed down by collision and all ultimately undergo neutron capture by nuclei present in the atmosphere. It is generally assumed that virtually all of the cosmic ray neutrons result in C^{14} production,[82] i.e., the N^{14} (n,p) C^{14} is the only reaction of importance. However, Hess *et al.*[83] conclude that only 67 per cent of cosmic ray neutrons are captured by this process, 16 per cent are captured by other processes, 17 per cent leak out of the atmosphere, and 0.2 per cent are captured by the earth.

49. The short-term variation of cosmic ray neutron flux with time, altitude and latitude is considerable (paras. 7, 11, 12, 14, 18), making it quite difficult to obtain an average value for neutron production to be used for the estimation of C^{14} production. The computation of the cosmic ray C^{14} production rate has been carried out by several workers[82-88] who have obtained values ranging from 1.3 to 3.1 atoms/cm²/sec. (i.e., average 2.2 atoms/cm²/sec which is equivalent to 3.4×10^{26} atoms C^{14}/y/earth's surface).

50. If the average value of the cosmic ray flux has been constant over the last tens of thousands of years (several C^{14} half-lives), the C^{14} activities in the carbon cycle would be in a "steady state" situation, for production of C^{14} would be balanced by decay of C^{14}. The specific activity of C^{14} would then be given by the following relation:

$$\text{Specific activity of } C^{14} \text{ (disintegrations/min/g carbon)} = \frac{\text{Production rate of } C^{14} \text{ (atoms/cm}^2\text{/min)}}{\text{Carbon in exchangeable carbon cycle (g/cm}^2\text{)}}$$

$$= \frac{2.2 \times 60}{8.1} \text{ dpm/g} \sim 16 \text{ dpm/g}$$

51. Experimental determinations of the specific activity of natural C^{14} in the biosphere have ranged from 12.9 to 15.3 dpm/g carbon,[89-93] the most recent measurement being 14.46 dpm/g.[89] The absolute disintegration rate for C^{14} in pre-1900 biospheric carbon may thus be taken to be 14 ± /dpm/g, which corresponds to a C^{14}/C^{12} ratio of 1.20×10^{-12}.

52. The constancy of the cosmic ray flux with time is of considerable interest, and three independent types of experiments have been carried out to give further information on this question. These three methods, which cover different time periods, are:

(*a*) Measurement of the C^{14} activity in biospheric samples of known age (time range of several thousands of years).[82,94-96]

(*b*) Comparison of radio-carbon and ionium ages of ocean sediments (time range of a few thousands to tens of thousands of years).[97]

(*c*) Comparison of observed activities of various cosmic ray induced radio-isotopes in meteorites (time range of hundreds to millions of years).[98]

53. All these data support the basic premise that the average cosmic ray flux has been essentially constant for hundreds of millions of years, and that any variation over the time period of interest for natural C^{14} (100-50,000 years) is less than a few per cent. It has been pointed out by Stuiver[199] that available evidence on sunspot activity (which is known to affect the cosmic ray level in the upper atmosphere) suggests some correspondence between sunspot activity and the C^{14} concentration in the atmosphere, as indicated by tree ring measurements.[95,100] Recent measurements of C^{14} variations in an 800 year old Kauri tree show[101] a gradual increase in the C^{14} content of the atmosphere over the last 850 years which could be attributed to an increase in the cosmic ray flux.

54. This natural C^{14} in the biosphere results in a negligible external dose-rate to man, and a larger, but still quite small, dose-rate due to its presence in the body tissues (para. 82).

Tritium

55. Tritium, H^3, a radio-active isotope of hydrogen with a half-life of 12.26 years, is, like C^{14}, continuously being produced in the atmosphere by cosmic rays, thus

* For discussion on C^{14} see also annex F, part I.

giving rise to concentrations of tritium in nature. These natural tritium levels have, since 1952, been modified by the addition of tritium to the atmosphere by nuclear weapons tests, especially by high yield fusion devices.

56. The tritium content of molecular hydrogen in the troposphere of the middle latitude regions of the northern hemisphere in 1949-1951,[102] 1954-1956[102] and mid-1959[103] respectively was about 30, 300 and 1500 $\mu\mu$c/g H. The resulting tissue dose-rate due to the incorporation of tritium in the body is considered in paragraph 84.

Beryllium-7 and other cosmic ray-produced nuclides

57. Other radio-active nuclides known to exist naturally owing to the interaction of cosmic ray neutrons with the atmosphere include Be^7, Na^{22}, P^{32} and S^{35}. Of these, Be^7, with a concentration of the order of 2×10^{-5} $\mu\mu$c/litre,[104,105] has the highest concentration. The tissue dose contribution from each of these nuclides is negligible.

V. Natural radio-activity in foodstuffs

58. The natural radio-activity in soil and water becomes transferred to man via the food-chain cycle. Study of this aspect requires measurement of activity levels in plants, some of which are used directly as human foods, while others, such as grasses, form the principal food of animals which in turn themselves become human food (F II). There is a wide range of activities in vegetation and there appears to be no simple correlation with the corresponding activities in soil for which the range is smaller. As there is not much information regarding the discrimination factors for the soil-food and food-man processes, the dose-rates to particular body organs are best related to measured concentrations in the particular organs.

Total alpha activity

59. A number of measurements have been reported of total α-activity in various dietary materials, but as the various daughter products in both the U^{238} and Th^{232} radio-active series may exist in different degrees of non-equilibrium, the individual isotopes should be identified in order to obtain the maximum information.

60. An extensive set of data on the total α-activity of foods has been published by Turner *et al.*,[106] and values vary from less than 1 up to 1.7×10^4 $\mu\mu$c/kg of food. In general, their measurements show low activities in milk products, fruit and vegetables, but higher values in cereals and nuts. They estimate that an adequate diet will not contain less than 2 $\mu\mu$c total α-activity per day, but it is obvious from the large range of values of activity in the different foods that small changes in eating habits can result in a large change in the intake of radio-activity. Mayneord[107] estimates that an adequate Western diet is not likely to contain less than 5 $\mu\mu$c of α-activity per day.

Radium-226

61. Regular three-monthly measurements[108] of the Ra^{226} content of the various foods in the average diet of three areas in the United States are being carried out by the Atomic Energy Commission's Health and Safety Laboratory and their results are given in table XIII. By using the Department of Agriculture's food consumption figures for the United States, Hallden and Fisenne[108] conclude that the average daily intake of Ra^{226} for the two surveys in New York City, Chicago and San Francisco is 2.4, 1.9 and 1.7 $\mu\mu$c respectively. Measurements of the Ra^{226} in the diet of infants in New York City[109] indicate that if the August 1960 samples are typical, then the intake of infants during the first year of their life is 212 $\mu\mu$c (0.6 $\mu\mu$c/d) of which about one-third comes from milk and one-half from cereals.

62. Muth *et al.*[62] have reported the Ra^{226} content of a wide variety of foods in Germany which give a range of activities 0.1 to 6 $\mu\mu$c/kg. Their values, some of which are given in table XIV, agree very well with the United States figures in table XIII. Muth *et al.* estimate that the daily intake of Ra^{226} is about 3 $\mu\mu$c, of which about 10 per cent is contributed through intake of Ra^{226} in water.

63. In addition to total α-activities for different foods, Turner *et al.*[106] reported the Ra^{226} activities for a few of the same samples. Some of these values are given in table XV for purposes of comparison with the United States and German results. It is thought[110] that the high values for cereals might be due to a contribution from Australian wheat for which total α-activity content has been reported for some samples to be higher than that for wheat from the United Kingdom and Canada.[111]

Thorium

64. No evidence has yet been found of the presence of Th^{232} in dietary materials. Mayneord and Hill[112] have published the α-spectrum of a sample of breakfast cereal made from whole wheat. This shows the two long-lived α-emitters, Ra^{226} and Th^{228} and their daughters. U^{238} and Th^{232} are absent and the Th^{228} may therefore be presumed to originate from Ra^{228} (a β-emitter which therefore does not appear in the spectrum) rather than by metabolic uptake of the element thorium. Later evidence[113] on the α-activities of leaf ash indicates uptake of Ra^{228} in preference to thorium. Turner *et al.*[106] reported both Ra^{226} and Th^{228} contents for twenty-three different food samples, and the average Th^{228}/Ra^{226} activity ratio for these was 0.9.

Pb^{210}, Bi^{210m} and Po^{210}

65. It has been observed[112,113] that the α-activity observed in certain samples of grass is mainly due to the presence of Po^{210}, accompanied by its parent Pb^{210} (β-γ emitter). Hill[114] suggests that this largely originates from a process in which Pb^{210}, resulting from the decay of atmospheric Rn^{222}, together with a fraction of the equilibrium amount of its descendant Po^{210} are deposited by rainfall directly on to the foliage. This fractionation is probably explained by the fact that both nuclides arise from the decay of a gaseous precursor. It is evident that Po^{210} or one of its precursors, such as Rn^{222} or Pb^{210}, may also be taken up directly from the soil. Since snow and even moderate rainfall can restrict the rate of escape of Rn^{222} from the surface of the soil (para. 24 above), it is clear that these factors could result in concentration of Pb^{210}, and in turn Po^{210}, being produced in the top layer. The relative uptake by vegetation from the soil and from direct deposition on the foliage probably varies from site to site, depending on parameters such as species of plant, soil drainage characteristics, depth of water table below the surface, etc.

Potassium-40

66. K^{40} is present in a fixed proportion (0.0118 per cent) of total potassium in all natural materials. The

potassium content of food varies considerably—for example, in the United Kingdom[115] values given for a very large number of samples of different types of food range from 0.1 per cent up to about 5 per cent (0.76 $\mu\mu$c K^{40}/g up to about 38 $\mu\mu$c K^{40}/g). Consequently potassium intake will be very dependent on diet and may show large variations between countries. For instance, Scott Russell[116] has pointed out that in the United Kingdom 23 per cent of the total potassium in diet originates from dairy produce and 35 per cent from potatoes, while in the United States the figures have been given as 38 per cent and 19 per cent respectively. The potassium intake for the United States based on per capita food consumption has been calculated to be approximately 2300 $\mu\mu$c/d.[117, 118]

VI. Natural radio-activity in the human body

67. The extremely low levels of naturally occurring radio-activity normally present in the human body make measurement of the individual radio-isotopes very difficult. *In vivo*, measurement of gamma rays is often used to measure the body potassium content. The total body Ra^{226} content can be estimated by measuring the rate of exhalation of radon and assuming a general value for the fraction of the total radon formed which escapes in the breath. This fraction is not accurately known and may indeed vary under different conditions. Ra^{226} and other nuclides can also be estimated by the analyses of autopsy samples.

Total alpha-activity

68. Turner *et al.*[119] measured the total α-activity of bones of persons native to Cornwall, London and Cumberland. The average value is 0.38 $\mu\mu$c/g ash, but individual results show large variations (figure 3). There appears to be a significant difference between values for Cornish bones and those from the London area or from Cumberland. The total α-activity in 10 Eskimo bones[107] showed a range from 0.18-0.97 $\mu\mu$c/g ash with an average of 0.61, and the rib of an Egyptian[107] who died almost 4,000 years ago gave a value of 0.34 $\mu\mu$c/g ash. Figure 3 indicates that for persons not occupationally exposed to α-activity, the concentration does not vary with age, but as the weight of the skeleton increases from birth to adult so the total α-activity in the skeleton increases in this period and then stays constant.

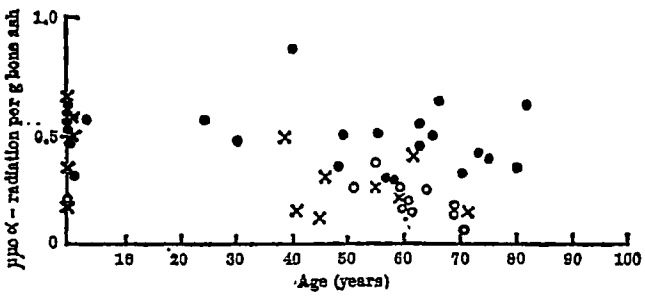


Figure 3. Human bone ash, total α activity. ●, Cornwall; ×, London; ○, Cumberland

69. Mayneord[120] finds a large variation of activity for different soft tissues, 0.15 to 1.00 $\mu\mu$c/g ash, but the average value of 0.52 $\mu\mu$c/g ash agrees very well with that obtained for skeleton ash. This leads Mayneord to conclude that in the normal human being, about 25 per cent of the α-emitting radio-active material is in the soft tissues.[107]

Radium-226

70. Ra^{226} is taken into the body through food, water and, to a lesser extent, air (para. 36). The total Ra^{226} content of normal human bodies has been determined by a number of workers, and values ranging from 3-1400 $\mu\mu$c obtained. These results are summarized in table XVI, along with data regarding the number of samples measured, and the average Ra^{226} content of drinking water in the area from which the samples were obtained. Where results are reported in terms of activity per gram ash, and individual total ash values are not given, it is assumed that a 70 kg man produces 2600 g skeletal ash and 400 g tissue ash. The results show[54] some correlation with the Ra^{226} content of drinking water when this source is predominant.

71. Walton *et al.*[121] measured the Ra^{226} concentrations in samples from up to 11 bones from each of 11 bodies in order to determine the variation within the skeleton. They concluded that there is no systematic difference in the radium content of the various bones of the average skeleton, at least to within $\pm$ 15 per cent. Departures from the mean of up to 50 per cent do occur in a few specimens. However, this degree of consistency within the various bones was not confirmed by Holtzman[122] in his measurements of both the Ra^{226} and Pb^{210} content of five bones from each of three persons who had been born in different states in the United States. These results are given in table XVII.

72. There is a distinct possibility that measurements on teeth may be used as an indicator of Ra^{226} bone levels, particularly if water concentrations are constant in the area. Lucas[54] found a value of 0.10 $\mu\mu$c/g ash for the average of Ra^{226} levels in teeth for nine persons which was almost identical to the 0.11 $\mu\mu$c/g ash found for bone from residents from the same city. The total α-activity levels in teeth obtained from the Royal Dental Hospital were also very similar to those in bones from persons who had lived in London.[107] Further, the activity of teeth from the inhabitants of Niue Island,[123] an area of high natural radiation (see section VII below), is of the order of ten times that of teeth from the inhabitants of normal areas.

73. The relative concentrations of radium in the skeleton and body tissues is uncertain. Muth *et al.*[62] suggest that 25 per cent of the total body radium is contained in the skeleton, whereas Hursh *et al.*[124] give a figure of 78 per cent and Lucas[54] 80-85 per cent. Results given by Hill[110] also tend to support this higher figure. The results for bone and muscle ash and wet tissue are given in table XVIII. No explanation has been given for the relatively high tissue values obtained by Muth, but total α-activity values in bone and soft tissue (para. 69) favour a skeletal content of about 80 per cent of the total body value.

74. Consideration of the above information indicates that the world average for the Ra^{226} total body burden is likely to be closer to 50 $\mu\mu$c than 100 $\mu\mu$c. In subsequent considerations, we will assume a conservative value of 75 $\mu\mu$c, of which 80 per cent (60 $\mu\mu$c) is in the skeleton.

Thorium

75. The presence of Th^{228} in human tissues[125] has been demonstrated by means of α-ray spectroscopy, but, as

with plant tissues (para. 64), the parent isotope of the thorium series, Th^{232}, has not yet been detected. It is therefore thought[125] that the Th^{228} originates from the metabolic uptake of radium in the form of Ra^{228} rather than uptake of thorium. Because the half-life of Ra^{228} is considerably less than that of Ra^{226}, it may be expected that the Ra^{228}/Ra^{226} activity ratio will be a maximum in newly fomed bone and will be less than this value in older bone. The magnitude of this effect is not known and, indeed, it does not appear to be sufficient to introduce an age effect into the total α-activity content of bones (figure 3). Mayneord *et al.*[125] suggest that 40 per cent of the total α-activity in adult bone is due to radiothorium, i.e., Th^{228}/Ra^{226} series activity ratio is approximately 0.7. Measurements reported by Stehney[126] on ashed bone samples from six subjects (average Ra^{226} skeletal content of about 90 $\mu\mu$c) gave an average Th^{228}/Ra^{226} series activity ratio of 0.4. This value is rather uncertain owing to the large fractional errors in the Th^{228} measurements. Using thoron in breath technique, Cullen[127] has found indications of much higher Th^{228} content of normal persons. It will be assumed that the world average Ra^{228} total body content is 50 $\mu\mu$c, of which 40 $\mu\mu$c is in the skeleton.

Pb^{210}, Bi^{210m} and Po^{210}

76. Various workers have determined Pb^{210}, Bi^{210m} and Po^{210} concentrations in human bone in excess of that expected from the Ra^{226} content. Holtzman[122] made measurements on samples of individual bones from forty-four humans and found an average skeletal Pb^{210} content of 360 $\mu\mu$c (corresponding mean Ra^{226} content was 100 $\mu\mu$c). He concluded that the origin of this Pb^{210} was mainly from food, to a slightly smaller extent from the atmosphere and a minor contribution only from drinking water. Hursh[128] obtained a value of 105 $\mu\mu$c for the mean skeletal Pb^{210} content of eighteen cadavers obtained in the New York area (average Ra^{226} content was 120 $\mu\mu$c). Hill and Jaworowski[129] measured the Pb^{210} content of bone samples from six subjects and found an average skeletal content of 160 $\mu\mu$c. It will be assumed that 200$\mu\mu$c Pb^{210} is the skeletal content of an average person.

Dose-rates for naturally occurring U and Th series

77. From the available data on natural radio-activity in humans, the average skeletal content of Ra^{226}, Ra^{228} and Pb^{210}, each in various states of equilibrium with its daughter products, has been chosen as 60 $\mu\mu$c, 40 $\mu\mu$c and 200 $\mu\mu$c respectively (paras. 74-76). The range of values for individuals is extremely large, e.g. for Ra^{226} it may be higher or lower than the average value by a factor of at least 25 (table XVI). However, for a population in a given small area, the range is likely to be much smaller.

78. The dose-rate to bone due to the naturally occurring uranium and thorium series is mainly due to the alpha-emitting components, and hence the irradiation pattern is extremely variable and depends on the size of the particular tissues being considered, their relation to the radio-active deposit and the ranges of the alpha particles. Spiers[130] has calculated the dose-rates to the osteocytes, the connective tissue lining the walls of the Haversian canal and the bone marrow originating from the Ra^{226} and Ra^{228} content of bone on the assumption that 35 per cent of the Rn^{222} and Rn^{220} formed is retained in the bone. The results for the average Ra^{226} and Ra^{228} contents, suggested in paragraph 77 and assuming 35 per cent and 100 per cent equilibrium respectively, are given in table XIX. Also included in the table are the estimated dose-rates to the same tissues resulting from a skeletal Pb^{210} content of 200 $\mu\mu$c (50 per cent equilibrium). The average dose-rates to the body tissues other than bone, assuming that the Ra^{226}, Ra^{228} and Pb^{210} activity is uniformly distributed and that the activity levels are 25 per cent of the values assumed for the skeleton of an average individual, are about 0.5, 0.8 and 0.3 mrem/y respectively from each of the above radio-isotopes.[130]

Potassium-40

79. *In vivo* measurements of total body potassium content have been made by a number of workers. The results of measurements by Anderson *et al.*[131] for 1,590 males and females as a function of age of the subject are given in figure 4. The concentrations vary considerably with age, and above an age of twelve years, a sex difference appears. Beyond twenty years of age, the percentage content in both males and females decreases in a similar manner but the male level is about 20 per cent higher than the female.

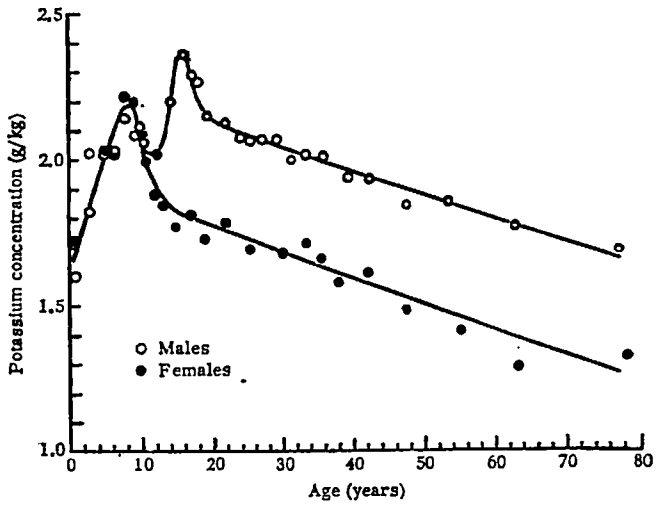


Figure 4. Average body potassium concentration of males and females as a function of age of subject

80. The potassium content of the various body organs varies considerably from about 0.05 to about 0.31 per cent, and the average for the whole body is about 0.2 per cent.[132] There is evidence that the potassium content of gonadal tissue is close to 0.20 per cent by weight, and using this figure, Rundo[133] estimates that the dose-rate to the testes is 17 and 2 mrem per year from the β- and γ-radiation respectively. This is in good agreement with the values of 16.5 and 2.3 mrem/y given in the 1958 report of the Committee and 18 and 2 mrem/y by Spiers.[52]

81. In trabecular bone, Spiers[53] quotes the potassium content as being between a value of 0.05 per cent for mineral bone and a value near to 0.2 per cent for bone-marrow, and gives the mean dose-rate as 15 mrem per year.

Carbon-14

82. The tissue dose rate due to natural C^{14} has been given as 1.0 mrem/y,[52] 1.5 mrem/y[134] and 1.6 mrem/y,[135] the difference between these values being essentially due to the values assumed for the specific disintegration rate

of natural C^{14} and the average beta energy per C^{14} disintegration. Taking 14 dpm/g carbon as the specific disintegration rate (para. 51), 50 keV as the average C^{14} beta energy[136-138] 18 per cent[1] as the average carbon content of the whole body of 70 kg weight, RBE equal to 1, then the average dose throughout the human body due to natural C^{14} is 1.06 mrem/y. The corresponding average dose-rate to soft tissue, with a carbon content of 12 per cent,[139] is 0.71 mrem/y, and to bone, with a carbon content of 27.8 per cent,[139] is 1.64 mrem/y.

83. Owing to the Suess Effect (F I 68) the dose reduction during the period 1850-1954 was approximately one mrem (about 0.01 mrem/y). If the use of fossil fuels up to year 2000 is as has been estimated,[140] the Suess Effect will then be nearly 10 per cent and the dose reduction over the period 1850-2000 would be approximately four mrem.

Tritium

84. The natural level of tritium in water in the middle latitude regions prior to the introduction of tritium due to weapon testing was of the order of 0.005-0.02 $\mu\mu c/g$ H.[141-144] Assuming soft tissue to be 100 per cent water, and that the average energy of tritium beta rays is 6 keV, this implies an average dose-rate to soft tissue of about 0.003 mrem/y (RBE = 1.7) or 0.006 mrem/y if an RBE of 3 is used (para. 3).[6]

VII. High natural radiation areas

85. In a small number of areas the dose-rate from natural background radiation is considerably higher than that experienced by populations in the major portion of the world. This high radiation background is due to the presence of larger than normal amounts of naturally occurring radio-active materials in the soil, drinking water, air, building materials, etc., and also to the cosmic ray altitude effect (paras. 13 and 14). It is considered[145] that studies of the populations in these areas are likely to contribute to the fund of biological knowledge and the ultimate specification of the genetic risks accruing from increasing exposure to ionizing radiation. This type of study is one of the few ways of studying the effects of ionizing radiation on human hereditary material.

High natural radio-activity in the earth's crust

86. There are five known major inhabited areas where there is increased radiation from soil or rock—these are in Brazil, France, India, Niue Island and the United Arab Republic. Data on the size, population and dose-rates of these areas are given in table XX.

87. The Kerala radiation measurements[146] were made inside three main types of houses in ten villages in the area. The results did not show any clear relation between radiation levels and structural differences in these houses. The average gamma dose-rates in the villages included in the survey revealed a twenty-fold variation (131-2,814 mrad/y), and the average value of 1,300 mrad/y is obtained by weighting values for each village according to its population.

88. There also exists the possibility of an additional significant radiation dose to the populations in these areas due to internal deposition of radio-active material. No published material on this aspect is available at present.

89. Certain natural springs have a very high natural radio-activity content and some of these are listed in table VII. However, these springs are not generally used as a permanent source of drinking water and so do not represent a continuous source of radiation exposure to large populations.

90. In those areas where the drinking water is of higher than normal activity, the populations are receiving additional radiation exposure and may be of interest for study of possible biological effects. One such area where a detailed survey is currently being made is in the Middle West region of the United States. Some of the drinking water in this area originates from wells which penetrate the deep sandstone formations and the water has concentrations up to 37 $\mu\mu c$ Ra^{226}/l. Results reported so far[147] indicate that drinking water containing more than 1 $\mu\mu c$ Ra^{226}/l is consumed by approximately 800,000 people, of whom about one half consume water containing more than 4 $\mu\mu c$ Ra^{226}/l. Of these, about 30,000 people consume water with activity in the range 10-37 $\mu\mu c$ Ra^{226}/l. The resulting range of Ra^{226} skeletal burdens[54] in people who have been consuming this water for long periods of time is given in table XVI.

High natural radio-activity in the air

91. The Rn^{222} and Rn^{220} content of air will generally be higher in areas of higher than normal natural radio-activity. For instance, the average Rn^{222} concentration at Bad Gastein,[148] which is situated in a deep valley containing many radio-active springs, is about 1 $\mu\mu c$/l compared with the average value of about 0.1 $\mu\mu c$/l for the European continent. Also, concentrations in confined volumes such as buildings will be considerably higher if ventilation is poor or absent. Under certain meteorological conditions, e.g., during fog, the natural radio-activity concentration in the air may increase by several factors of ten.

High natural radio-activity in buildings

92. Aside from high radiation in buildings due to the increased Rn^{222} and Rn^{220} content of the air (para. 91), dose-rates may be increased owing to the high natural radio-activity of the construction materials. Granite and light-weight concrete containing alum shale are common building materials which often result in particularly high radiation levels inside buildings, as can be seen from the dose-rates give in table V.

High altitude areas

93. As discussed in paragraphs 13 and 14, the cosmic ray intensity increases markedly with altitude. This raises the possibility of study of populations living at altitudes of the order of 3,000 metres where the total cosmic ray dose-rate due to the neutron and ionizing components may be of the order of 50-150 mrem/y. Table XXI gives some of the high altitude areas in the world along with their altitude, latitude, population[145] and cosmic ray contribution to tissue dose-rate estimated on the basis of the figures given in table I.

VIII. Summary of exposure data

94. The mean gonad and skeletal dose-rates from natural sources of irradiation under "normal" conditions are given in table XXII. (For information on high natural radiation areas, reference should be made to section VII above.) The suggested typical value for the total cosmic radiation tissue dose-rate, 50 mrem/y, is the value at sea level for middle latitudes (para. 8 and table I). The terrestrial gamma-radiation results from the gamma activities present in the soil, buildings and air, and the average tissue dose-rate of 50 mrem/y takes into account absorption of radiation by the outer tissues

and also the relative time spent indoors and outdoors. Internal irradiation of man arising from the presence in the body organs of naturally occurring radio-active nuclides—K^{40}, C^{14}, H^3 and various decay products of the uranium and thorium series—is extremely dependent on geometrical considerations and average dose-rates in various tissues are given in table XXII. The dose-rate to the lungs due to the natural radio-activity content of the air is not presented in table XXII but, as mentioned in paragraph 42 above, this dose-rate is higher than that to any other body tissue. The dose-rates due to H^3 are very small in comparison with those due to the radionuclides given.

95. The total dose-rates in the body tissues given in table XXII may be considerably in error owing to uncertainties of the individual components. These uncertainties are discussed in the text of the present annex, and it is anticipated that more truly representative values will become apparent as further investigations are made. It is felt that where a representative value for the natural background dose-rate to individuals in "normal" areas is required, the best value which can be recommended at the present time is about 130 mrem/y.

TABLE I. VARIATION OF TOTAL COSMIC RAY CONTRIBUTION TO TISSUE DOSE-RATE WITH ALTITUDE AND LATITUDE

Altitude (km)	*Total cosmic radiation tissue dose rate in mrem/y**		
	*Equator***	*30°***	*50°***
0	35	40	50
1	60	70	90
2	100	130	170
3	170	220	300
4	260	360	500
5	400	580	800
10	1,400	2,300	4,500
15	3,000	5,000	11,000
20	3,500	6,000	14,000

* See annex A for RBE values used.
** Distinction between geographical and geomagnetic latitudes is not justified.

TABLE II. PHYSICAL DATA FOR RADIATION FROM CERTAIN NATURALLY OCCURRING RADIO-ACTIVE NUCLIDES[149]

Nuclide		*Radio-active half-life*	*Particle energies in MeV and percentages where known**	*γ energies in MeV and percentages where known**
Symbol	*Common name*			
H^3	Tritium	12.26 y	β^- 0.0186(100)	No γ**
Be^7	Beryllium-7	53 d	EC	0.477(12)
C^{14}	Carbon-14	5,760 y	β^- 0.165(100)	No γ
Na^{22}	Sodium-22	2.58 y	β^+ 0.54(90)EC(10)	1.28(100)
P^{32}	Phosphorus-32	14.3 d	β^- 1.71	No γ
S^{35}	Sulphur-35	87 d	β^- 0.167	No γ
K^{40}	Potassium-40	1.3×10^9y	β^- 1.32(89)EC(11)	1.46(11)
Rb^{87}	Rubidium-87	4.8×10^{10}y	β^- 0.27	No γ
La^{138}	Lanthanum-138	1.1×10^{11}y	EC(70), β^- 0.20(30)	1.43(70), 0.81(30)
Sm^{147}	Samarium-147	1.2×10^{11}y	α2.20	No γ
Lu^{176}	Lutecium-176	2.2×10^{10}y	β^- 0.42(100)	0.31(100), 0.20(100), 0.088(100)
U^{238}	Uranium I	4.51×10^9y	α4.19, —, CE, SF	0.048(23)
Th^{234}	Uranium X_1	24.1 d	β^- 0.19(65), 0.10(35)	0.092, 0.063, 0.029
Pa^{234m}	Uranium X_2	1.18 m	β^- 2.31, —(99), IT(1)	0.043, 0.23—1.83
U^{234}	Uranium II	2.50×10^5y	α4.77(72), 4.72(28), —, SF	0.053, 0.118
Th^{230}	Ionium	8×10^4y	α4.68(76) 4.61(24)	0.068, 0.142—0.254
Ra^{226}	Radium	1,620 y	α4.78(95), 4.59(4), —	0.187(4), —
Rn^{222}	Radon	3.823 d	α5.49(99+), 4.98(0.08), 4.83	0.51(0.08).
Po^{218}	Radium A	3.05 m	α6.00(99+) β^- (0.02)	No γ
Pb^{214}	Radium B	26.8 m	β^- 1.03(6), —	0.352, 0.295, 0.053—0.259
Bi^{214}	Radium C	19.7 m	β^- 3.18, —(99+)α5.51, —(0.04)	0.61, 1.12, 1.76, 0.45—2.43
Po^{214}	Radium C^1	1.6×10^{-4}s	α7.68	No γ
Pb^{210}	Radium D	20 y	β^- 0.017(85),0.063(15)	0.046(15)
Bi^{210m}	Radium E	5.0 d	β^- 1.16(99+)α(0.02)	No γ
Po^{210}	Radium F	138.4 d	α5.30, —	0.80(0.001)
Th^{232}	Thorium	1.41×10^{10}y	α4.01(76), 3.95(24)	0.059(24)
Ra^{228}	Mesothorium I	6.7 y	β^-<0.02	No γ
Ac^{228}	Mesothorium II	6.13 h	β^- 1.11(53), 0.45—2.18	0.057, 0.10, 0.91, 0.078—1.64
Th^{228}	Radiothorium	1.91 y	α5.42(71), 5.34(28), —	0.084, 0.212, 0.137, 0.169
Ra^{224}	Thorium X	3.64 d	α5.68(95), 5.44(5)	0.241(5)
Rn^{220}	Thoron	55 s	α6.28(99+), 5.74(0.3)	0.54(0.3)
Po^{216}	Thorium A	0.16 s	α6.78	No γ
Pb^{212}	Thorium B	10.64 h	β- 0.34(84), 0.58(12), —	0.239(84), 0.30, 0.115—0.41
Bi^{212}	Thorium C	60.5 m	β^- 2.25, —(64), α6.09, —(36)	0.040(25), 0.73(6), 1.62, 0.124—22
Po^{212}	Thorium C^1	3×10^{-7}s	α8.78	No γ
Tk^{208}	Thorium C^{11}	3.1 m	β^- 1.80(47), 1.0—2.38	2.61(100), 0.58(77), 0.51(30), 0.040—1.09
U^{235}	Uranium-235	7.1×10^8y	α4.18—4.56, SF	0.185(55), 0.143(12), 0.095(9), 0.074—0.38
Np^{237}	Neptunium-237	2.2×10^6y	α4.52—4.87	0.087(14), 0.029(14), 0.057—0.200
Pu^{239}	Plutonium-239	24,300 y	α5.15(72), 5.13(17), 5.10(11), —, SF	0.013(17), 0.051, 0.038—0.42(<0.001)

* Beta and gamma energies (MeV) are limited to four plus a range, given in order of decreasing intensity. When known, the percentage of disintegration (intensity) giving a particular energy appears in parenthesis following the energy. The dash between two energies indicates that there are three or more radiations in that range of lesser intensities than those already given. A dash following several energies indicates additional energies of lesser intensity. Percentages applied to gamma energies are transition intensities rather than photon intensities; they also include conversion-electron intensities.

** "No γ" means that gammas have been searched for but not found (excepting perhaps X-rays from electron capture).

C E = conversion electron.
E C = electron capture.
I T = isomeric transition.
S F = spontaneous fission.

TABLE III. U^{238}, Th^{232}, Ra^{226} AND K^{40} CONTENTS IN $\mu\mu C/G$ IN VARIOUS ROCKS (MEAN VALUES)

Type of rock	U^{238}	Th^{232}	Ra^{226}	K^{40}	*Reference*
Igneous rocks	0.5				38
	1.4	1.3	1.3	22	150
		3.5	3.7	25	151
Granites		2.3	3.1	29	41
				30	57
	1.4				152
			2.6		153
	3	13			154
Basalts		1.0	1.1	11	41
				8	57
			0.5		153
Volcanic rocks:					
Basic lavas	0.9	~3			155
Acidic lavas	5	~15			155
Sedimentary rocks			0.25		153
Sandstones	0.4	0.7	0.7	9	150
Sandstones			0.3		41
Limestone	0.5	0.15	0.4	2.3	150
Limestone		0.1	0.7	2.5	41
Limestone			1	2.5	42
Alum shales, Sweden		0.1	60		41
Alum shales, Sweden		0.17	60	29	42
Shales	0.5	0.14	0.4	2.3	150
Bituminous shale, U.S.A.	22				152
Phosphate rocks, Florida	40				152
Phosphate rocks, Nauru	20	0.8			156
Phosphate rocks, N. Africa	4	1.0			153
Phosphate rocks, N. Africa	8				57

TABLE IV. MEASURED TERRESTRIAL GAMMA DOSE-RATES OUT OF DOORS IN VARIOUS COUNTRIES

Country	*Dose rate in air mrad/y*	*Comment*	*Reference*
Austria	47–56		157
France	45–90	Limestone	
	180–350	Granites and shales	158
Japan	23–37	Kanto loam	159
	79–119	Granite areas	159
Sweden*	70–100	Stockholm street	160
	60–120	Igneous rocks	160
	50	Clay	160
UK	18–61	Sedimentary rock or clay	53
	77–155	Granite areas	53
USA*	45–130	Measurements in 23 States	161

* Values obtained by subtraction of an experimentally determined value of 28 mrad/y to allow for cosmic radiation at sea level and appropriately larger quantities at various altitudes.

TABLE V. MEASURED TERRESTRIAL GAMMA DOSE-RATES IN AIR INSIDE BUILDINGS IN VARIOUS COUNTRIES

Country	*Dose rate in air mrad/y*	*Comment*	*Reference*
Austria	47–56	Wooden house	157
	65–75	Brick or concrete	157
	75–112	Granite	157
Japan	48–68	Concrete	162
	29–41	Wooden (Tokyo)	159
	80–100	Wooden (Kyoto)	159
Sweden*	48–57	Wooden	42
	99–112	Brick	42
	158–202	Light weight concrete (containing alum shale)	42
UK	85–300	Granite	163
	32–57	Other than granite	163
USA	29–90	17 houses in New York area	161

* Values obtained by subtraction of 28 mrad/y to allow for cosmic radiation (but this correction is probably too large in the case of multistorey buildings).

TABLE VI. MEAN DOSE-RATES FROM TERRESTRIAL GAMMA-RADIATION ONLY IN FOUR LOCALITIES IN UNITED KINGDOM[53]

Locality	Mean dose-rate in air mrad/y		Mean dose-rate in human tissues mrad/y	
	Out of doors	In houses	Gonads	Bone-marrow
Edinburgh	48.5	60.0	36	37
Dundee	63.0	67.2	42	43
Aberdeenshire	69.5	81.5	50	51
Aberdeen	104.0	85.3	57	58

TABLE VII. NATURALLY OCCURRING RADIO-ACTIVITY IN PUBLIC WATER SUPPLIES

Water source	Ra^{226} concentration μμc/l	Rn^{222} concentration μμc/l	Reference
Austria Bad Gastein	0.6		167
Germany, 7 cities	0.03–0.3	Up to 220	62
Sweden, 2 cities	0.2–1		169
UK, ground and surface water	Up to 0.7	Up to 200	61
Cornish waters	Up to 2.4	Up to 3,000	61
Devon waters		Up to 13,000	170
USA, tap water for 41 cities	Up to 0.2 (average 0.04)		171
Deep sandstone well, Ill.*	Up to 37		172
Surface water, Ill.	< 0.2		56
USSR, freshwater (mean)	1		173

* See section VII.

TABLE VIII. NATURALLY OCCURRING RADIO-ACTIVITY OF NATURAL WATERS AND SPRINGS

Water source	U^{238} concentration μμc/l	Ra^{226} concentration μμc/l	Rn^{222} concentration μμc/l	Reference
Germany, river water		0.07–0.8		62
UK, river water		0.01	0.2–0.3	164
USA, river water	0.005–0.01	0.03 (1–3)[21]		57
Lake water	1.7			57
Ground water	Up to 40	Up to 22		165
Austria, springs	Up to 4		Up to 10^5	166, 167
France, springs		Up to 139	Up to 10^5	158
Germany, springs		0.07–18	Up to 10^3	62
Japan, springs	Up to 0.3[57]		Up to 7×10^5	153
Lebanon, springs			Up to 6×10^3	39
UK, springs		Up to 12	Up to 7×10^2	61
USA, springs			Up to 3×10^5	153
USSR, springs and brooks	Up to 3			168

TABLE IX. CONCENTRATIONS OF Rn^{222} AND Rn^{220} IN FREE AIR AT GROUND LEVEL IN VARIOUS REGIONS

Average concentration in μμc/l

Country	Rn^{222} (radon)	Rn^{220} thoron	Reference
Austria	0.1–0.3		157
Czechoslovakia	0.03	0.002	69
France	0.2	0.006	158
Holland (Amsterdam)	0.13		174
Sweden	0.1		42
UK	0.3		53
USA	Up to 3 (smog conditions)		175
	0.25	0.004	175
USSR	0.005–0.5	0.05	173

TABLE X. AVERAGE CONCENTRATIONS OF Rn^{222} AND Rn^{220} IN AIR OF VENTILATED AND UNVENTILATED SWEDISH APARTMENTS AND THE CORRESPONDING CALCULATED AVERAGE DOSE RATES TO LUNGS[42]

Outer wall construction	Average concentration in μμc/l				Average dose rate to lungs in mrem/y			
	Rn^{222}		Rn^{220}		Rn^{222}		Rn^{220}	
	A*	B**	A*	B**	A*	B**	A*	B**
Wood	0.527	0.537	0.0278	0.136	263	73	185	52
Brick	0.909	0.913	0.0910	0.450	453	128	582	173
Light weight concrete (containing alum shale)	1.86	1.86	0.0959	0.461	930	262	640	178

* Condition A: Assuming equilibrium.

** Condition B: High ventilation rate, 10^{-3} sec.$^{-1}$.

TABLE XI. AVERAGE Rn^{222} CONTENT INDOORS AT VARIOUS LOCALITIES[42]

Country and locale	Average Rn concentration μμc/l
Canada, laboratory	0.05–3
UK	0.08
Sweden:	
Wooden apartments	0.5
Brick apartments	0.9
Concrete apartments	1.9
USA, laboratory	0.9–1.0
USA, laboratory	<0.1
USA, laboratory	0.13

TABLE XII. AVERAGE CONCENTRATION OF Pb^{210}, Bi^{210m} AND Po^{210} IN AIR AT GROUND LEVEL IN VARIOUS REGIONS

Region	Rn^{222} daughter product	Average concentration in air μμc/l	Reference
UK	Pb^{210}	3×10^{-6}	176
USA	Pb^{210}	10^{-5}	70
USSR	Pb^{210}	5×10^{-3}	173
USSR	$Bi^{210}m$	4×10^{-6}	173
UK	Po^{210}	0.4×10^{-6}	176

TABLE XIII. RADIUM-226 IN FOODSTUFFS (μμc Ra^{226} PER KG ORIGINAL MATERIAL)

Food type	New York City		Chicago		San Francisco	
	Survey 2 June 1960	Survey 3 Oct. 1960	Survey 1 May 1960	Survey 2 Sept. 1960	Survey 2 Aug. 1960	Survey 3 Jan. 1961
Whole wheat bread	3.2	1.2	3.5	2.9	2.8**	2.8
White bread	3.2	1.5	3.3	2.0	2.9	2.5
Flour—white	2.7	1.7	2.4	2.0	1.34	0.83
Milk—liquid	0.25	0.24	0.24	0.22	0.22	0.2
Potatoes	2.0	2.5	1.4	0.77	1.0*	2.0
Macaroni	2.1	1.8	1.6	1.9	1.2	1.7
Dried beans	6.1	3.2	7.0*	2.5	2.3	4.1
Canned vegetables	2.2	0.54	1.8	1.1	0.91	1.0
Fresh vegetables	2.4	1.2	2.2	0.57	0.66	0.84
Root vegetables	3.4	2.3	2.0*	1.8	2.6*	2.4
Canned fruit	0.37	0.37	1.2	0.26	0.5	0.73
Fruit juices	1.6	0.49	0.68	0.86	0.71	0.62
Fresh fruit	1.5	2.8	1.4	0.57	0.91	0.65
Rice	1.5	1.0	0.7	0.37	0.63	0.8
Eggs	4.1	7.9	2.7	2.7**	2.6	1.9
Fresh fish	1.2	0.68	0.71	1.0	0.8	1.2
Shellfish	1.2	1.1	2.5	1.7	2.0	1.0
Meat	0.44	0.47	0.45	0.64	0.81	0.55
Poultry	0.73	0.86	0.79	1.4	1.9	0.49

* Data corrected by barium recovery as well as strontium recovery.
** Missing sample. Paired value used for computing sums.

TABLE XIV. Ra^{226} CONTENT OF VARIOUS FOODS IN GERMANY[62]

Food	μμc/kg food	food	μμc/kg food
Bread	2.6	Carrots	1.6, 1.7, 6.1
White bread	1.7, 3.3	Apples	0.9
Wheat flour	2.7	Eggs	3.1
Milk	0.3	Fish	2.8, 4.0, 4.0, 6.3
Potatoes	0.6, 1.0	Pork, beef	0.8, 1.5, 0.8, 0.8
Cabbage	1.0, 2.4	Tap water	0.03–0.34 (av 0.19)

TABLE XV. Ra^{226} CONTENT OF VARIOUS FOODS IN UNITED KINGDOM[106]

Food	μμc/kg food	Food	μμc/kg food
Cereal	25, 62, 68	Fresh fish (plaice)	1.5
Tinned pears	1.1	Cockles and mussels	18.2, 5.7
Egg	2.0	Veal, Sausage	0.9, 2.0

TABLE XVI. TOTAL BODY Ra^{226} CONTENTS

Sampling locality	Number of bodies	Concentration Ra^{226} in tap water μμc/l	Ra^{226} body content μμc		Type of sample	Reference
			Range	Mean		
USA, Rochester, N.Y.	20*	0.04	38–353	118	Whole body ash	177
USA, Rochester, N.Y.	14*	0.04	47–130	87	Whole body ash	178
USA, Rochester, N.Y.	9	0.04	15–65	30	Body organ ash	124
USA, Northwest Pacific area	50	0.001	13–139	47	Whole body ash	179
Germany, Frankfurt on Main	15	0.14–0.31	130–790	330	Body organ ash	180
Germany, Frankfurt on Main	Up to 56	0.2	—	130 (35 in skeleton)	Body organ ash	62
USA, New York	140	0.04	3–150	24	Whole skeleton ash	121
Six different countries	21	—	—	40	Single bone ash	121
13 different countries	499 15 samples	—	—	33	Bone ash—composite sample	121
USA, Prisoners, 4 mo. detention	11	3.4	—	100	*In vivo*, radon in breath	181
USA, Prisoners, 7.6 yr. detention	8	3.4	—	202	*In vivo*, radon in breath	181
USA, Prisoners, 19.7 yr. detention	11	3.4	—	236	*In vivo*, radon in breath	181
USA, Lockport boys	8	8	—	368	*In vivo*, radon in breath	181
USA, Chicago boys	7	0.03	—	36	*In vivo*, radon in breath	181
USA, low activity water	42	< 0.1	15–81	36	Single bone ash	54
USA, high activity water	34	0.1–10.5	36–1400		Single bone ash	54

* Check series using different methods of measurement.

TABLE XVII. Ra^{226} AND Pb^{210} IN BONES OF SUBJECTS FROM ROCHESTER, N.Y., USA[122]

	Concentration in (μμc/g ash ± 90 per cent confidence level) × 10^8					
	Born in Nebraska, lived in Rochester, ages 1–68		Born in Connecticut, lived in Rochester, ages 14–43		Born in Florida, lived in Rochester, ages 49–52	
	Ra^{226}	Pb^{210}	Ra^{226}	Pb^{210}	Ra^{226}	Pb^{210}
Skull	70 ± 4	201 ± 15	51 ± 2	131 ± 9	32 ± 3	366 ± 19
	70 ± 4	419 ± 14	100 ± 7		27 ± 3	1,330 ± 21
Tibia	12 ± 3	296 ± 13	25 ± 2	90 ± 9	26 ± 2	78 ± 6
Joint	16 ± 1	152 ± 7	25 ± 2	83 ± 8	27 ± 3	71 ± 7
Jaw	12 ± 1	93 ± 5	28 ± 2	49 ± 4	30 ± 3	77 ± 6
Teeth	19 ± 3	18 ± 4				

TABLE XVIII. Ra^{226} CONTENT OF BONE AND MUSCLE

Tissue	Number of samples	Ra^{226} content/g ash ($\times 10^{-3}$ μμc)	Ra^{226} content/g wet tissue ($\times 10^{-3}$ μμc)
Vertebrae[124]	10	10.7	3.4
Clavicle[124]	10	9.2	1.1
Skeletal muscle [124]	10	5	0.05
Tibia shaft[62]	56	12	5.4
Femur[62]	37	11	4.8
Muscles[62]	12	245	2.5
Bone[54]	3	14.6	—
Muscle[54]	3	12.2	—

TABLE XIX. MEAN DOSE-RATES (MREM/Y, RBE=10) TO VARIOUS TISSUES OF NORMAL HUMANS[130]

Body tissues	*Skeletal Ra^{224} and daughters (60 μμc) (35% equilibrium)*	*Skeletal Ra^{226} and daughters (40 μμc) (equilibrium)*	*Skeletal Pb^{210} and daughters (200 μμc) (50% equilibrium)*
Osteocytes (5 μ diameter)	10	16	6.6
Haversian canal (10 μ lining, 50 μ diameter)	5.4	8.6	3.6
Trabecular marrow	0.6	1.0	0.4

TABLE XX. SPECIAL AREAS OF HIGH EXTERNAL RADIATION TO RADIO-ACTIVITY FROM SOIL OR ROCK

Area	*Approximate population*	*External dose-rate in air (Cosmic plus terrestrial)*	*Measuring instruments*
Monazite area in States of Rio de Janeiro and Espirito Santo, Brazil—sequence of coastal strips, each several km long and several hundred metres wide	30,000	Average 500 mrad/y, peak 1,000 mrad/y[132]	Ionization chamber scintillation counter
Mineralized volcanic intrusives in States of Minas Gerais and Goias, Brazil—6 km^2 in a dozen scattered places	1 village with 350 inhabitants, pasture land and scattered farms	Average 1,600 mrad/y, peak 12,000 mrad/y[132]	Ionization chamber scintillation counter
Primitive granitic, schistous and sandstone areas of France—area includes about one-sixth of French population	7,000,000	180–350 mrad/y[158]	Geiger counter and scintillation counter (Na. I and plastic phosphor)
Monazite area in Kerala and Madras States, India—approximately 200 km long and several hundred metres wide	100,000	Population weighted mean 1,300 mrad/y plus about 200 mrad/y beta rays[146]	Ionization chamber
Niue Island, Pacific—volcanic soil and unusually high radio-active content of plants	4,500	Maximum external radiation 1,000 mrad/y. High total α-radio-activity content 50–360 μμc/g in the main foodstuff—taro[122]	—
Monazite areas of Northern Nile Delta region, UAR	"Highly populated"	300 and 400 mrad/y in 2 villages; 4 other villages in same area 110 to 150 mrad/y[133]	Scintillation counter

TABLE XXI. COSMIC RAY DOSE-RATES IN HIGH ALTITUDE AREAS AND CORRESPONDING POPULATIONS[145]

Area	*Altitude (metres)*	*Latitude*	*Cosmic ray contribution to tissue dose-rate (based on table I) mrem/y*	*Population*
La Paz, Bolivia	3,630	16°S	270	319,600
Quito, Ecuador	2,850	0°	160	212,873
Bogota, Colombia	2,640	4°N	150	325,658
Cerro de Pasco, Peru	4,259	10°S	330	19,187
Lhasa, Himalayan Area	3,684	30°N	310	~20,000

TABLE XXII. BODY TISSUE DOSE-RATES DUE TO EXTERNAL AND INTERNAL IRRADIATION FROM NATURAL SOURCES OF RADIATION IN "NORMAL" REGIONS

Source of irradiation	*Dose rate in mrem/y (see paragraphs 2–3 for RBE values)*			*Reference in text*
	Gonad	*Haversian canal*	*Bone marrow*	
External irradiation:				
Cosmic rays (including neutrons)...	50	50	50	Paragraph 8, Table I
Terrestrial radiation (including air).	50	50	50	Paragraph 31
Internal irradiation:				
K^{40}.....	20	15	15	Paragraphs 80–81
Ra^{226} and decay products (35 per cent equilibrium).....	0.5	5.4	0.6	Paragraph 78
Ra^{226} and decay products (equilibrium).....	0.8	8.6	1.0	Paragraph 78
Pb^{210} and decay products* (50 per cent equilibrium).....	0.3	3.6	0.4	Paragraph 78
C^{14}.....	0.7	1.6	1.6	Paragraph 82
Rn^{222} (absorbed into bloodstream)..	3	3	3	Paragraph 41
TOTAL.....	125	137	122	

* Pb^{210} in excess of that expected from Ra^{226} and decay products in 35 per cent equilibrium.

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