1 1977

Proceedings of the International Symposium on areas of high natural radioactivity. Academia Brasileira de Ciencias, Rio de Janeiro, 1977.

06.7718

DOSIMETRIC IMPLICATIONS OF THE EXPOSURE TO THE NATURAL SOURCES OF IRRADIATION

D.J.BENINSON, A.BOUVILLE

United Nations Scientific Committee on the Effects of Atomic Radiation, Commissariat à l'Energie Atomique, France

B.J.O'BRIEN and J.O.SNIHS

Institute of Nuclear Physics, New Zealand National Institute of Radiation Protection, Sweden

Man has been continuously exposed to natural radiation since his appearance on earth and, until less than a century ago, was exposed to natural radiation only. Even now, despite the widening use of radiation-producing devices, the widespread radioactive contamination from nuclear weapon tests and the increasing applications of nuclear energy and radio-isotopes, natural sources are the main contributors to the radiation exposure of most of the human population and are likely to remain so in the foreseeable future.

Natural radiation is of two origins, extraterrestrial and terrestrial. Extraterrestrial radiation originates in outer space as primary cosmic rays and reaches the atmosphere, with which the incoming energy and particules interact, giving rise to secondary cosmic rays -- those to which living beings on the earth's surface are exposed.

Terrestrial radiation is emitted from radioactive nuclides present in varying amounts in all soils and rocks, the atmosphere and the hydrosphere, and from those radio-nuclides that, transferred to man through food chains or by inhalation, are deposited in his tissues. Terrestrial radio-activity, therefore, leads to both external and internal exposure.

The purpose of this paper is to summarize the existing information on man's exposure to natural sources. Most of the information has been taken from the 1972 Report of the UNSCEAR Committee; some of the dose estimates found in that Report have been updated in the light of the available results of more recent studies.

EXTERNAL IRRADIATION

1. COSMIC RAYS

The high-energy radiations which enter the earth's atmosphere from outer space are known as primary cosmic rays. Their origin is still not yet completely determined but it is known that most of the observed radiation originates in our galaxy. Those primary galactic cosmic rays largely consist of high-energy protons which enter the solar system from interstellar space. Together with protons are ^{4}He ions in the proportion of about

10 per cent. Smaller proportions of heavier particles are also present, together with electrons, photons and neutrinos. Moreover, during periods of solar activity the sun produces solar cosmic rays which consist mostly of non-relativistic protons.

When the primary cosmic-ray particles enter the atmosphere, those with higher energy undergo nuclear reactions, while those with lower energy lose energy by ionization. When reacting with nuclei of atoms present in the air they produce neutrons and protons, in addition to pions and kaons. Many of the secondary particles have sufficient energy to initiate whole sequences of further nuclear reactions with nitrogen and oxygen nuclei. The initial high-energy reactions are called spallation reactions and quite a variety of reaction products are formed (Table 1); with regard to external irradiation at ground level, the most important of those reaction products, called cosmogenic radionuclides in this paper, are probably ^{7}Be, ^{22}Na and ^{24}Na. However, the external dose arising from those radionuclides is completely insignificant when compared to the doses from cosmic rays.

TABLE 1

Cosmic Ray Produced Radio-Active Nuclides (UNSCEAR, 1972)

Radionuclide	Calculated atmospheric production rate (atoms cm^{-2} s^{-1})	Half-life	Maximum energy of beta radiation (keV)
^{3}H	0.20	12.3 y	18
^{7}Be	$8.1\ 10^{-2}$	53 d	Electron capture
^{10}Be	$4.5\ 10^{-2}$	$2.5\ 10^{6}$ y	555
^{14}C	2.5	5,730 y	156
^{22}Na	$8.6\ 10^{-5}$	2.6 y	545 (β^{+})
^{24}Na	$3.0\ 10^{-5}$	15.0 h	1,389
^{28}Mg	$1.7\ 10^{-4}$	21.2 h	460
^{26}Al	$1.4\ 10^{-4}$	$7.4\ 10^{5}$ y	1,170
^{31}Si	$4.4\ 10^{-4}$	2.6 h	1,480
^{32}Si	$1.6\ 10^{-4}$	700 y	210
^{32}P	$8.1\ 10^{-4}$	14.3 d	1,710
^{33}P	$6.8\ 10^{-4}$	25 d	248
^{35}S	$1.4\ 10^{-3}$	87 d	167
^{38}S	$4.9\ 10^{-5}$	2.9 h	1,100
^{34m}Cl	$2.0\ 10^{-4}$	32.0 min	2,480
^{36}Cl	$1.1\ 10^{-3}$	$3.1\ 10^{5}$ y	714
^{38}Cl	$2.0\ 10^{-3}$	37.3 min	4,910
^{39}Cl	$1.4\ 10^{-3}$	55.5 min	1,910
^{39}Ar	$5.6\ 10^{-3}$	270 y	565
^{81}Kr	$1.5\ 10^{-7}$	$2.1\ 10^{5}$ y	Electron capture

The doses from cosmic rays consist of several components arising from the muons, the electrons, the pions, the protons and the neutrons present in the radiation field. O'Brien and McLaughlin (1970) have calculated the ionization produced by the different cosmic-ray components at various altitudes. The variation of the contribution of the different cosmic-ray components to the tissue dose five centimetres inside an isotropically-irradiated phantom as computed by O'Brien and McLaughlin is shown on figure I. These

results are very instructive for they show that, below five kilometres, most of the dose arises from muons, with electrons making the next largest contribution. Above 10 kilometres, electrons and protons are the major contributors to dose.

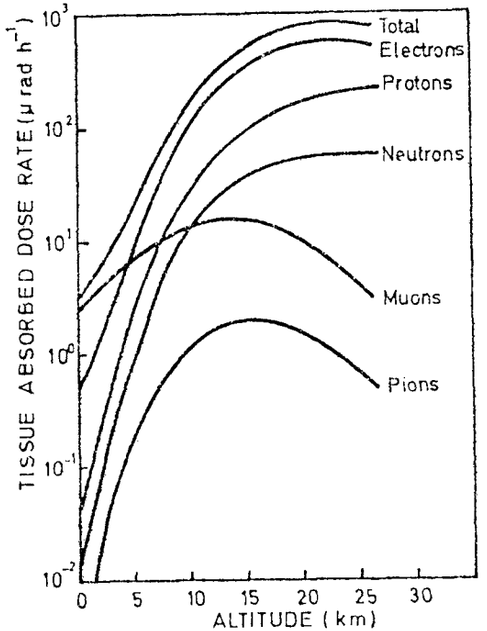

Fig. 1. Computed dose rate (5 cm inside an isotropically irradiated tissue slab) from the different components of cosmic rays as a function of altitude.

As this paper deals with the doses received by the population of various countries of the world, the reference level adopted will be the sea level.

In its 1972 report, the UNSCEAR Committee estimated the air absorbed dose rate in air from the ionizing component at sea level to be 3.2 μrad h^{-1} from on ionization rate of 2.14 pairs cm^{-3} s^{-1} and the assumption that one ion pair cm^{-3} s^{-1} is equivalent to 1.5 μrad h^{-1}; the variation with latitude was neglected. Since the radiation is very penetrating and the mass absorption coefficients for tissue and air are very close, the tissue absorbed dose rates are in this paper assumed to be the same as the air absorbed dose rates in air. The annual dose to any body organs and tissues may thus be calculated just by multiplying the air dose rates by the time period of one year. The annual dose for the ionizing component is then found to be 28 mrad. It should be noted however that the dose rate indoors might be significantly lower than that outdoors because of the shielding effect of the building materials. It is estimated that the attenuation by the various types of buildings ranges from nearly zero for woodframe houses to more than 50 per cent for lower floors in multi-storied offices or apartment buildings (NCRP, 1974b).

In its 1972 report, the UNSCEAR Committee derived the dose rates from the neutron component from computed absorbed dose rates in 30- cm tissue slabs. A value of

0.35 mrad was adopted for the annual tissue absorbed dose at sea level at 40° latitude and further north. In equatorial regions, if would be about 0.2 mrad.

Doses from high levels of cosmic radiation – At sea level, the external dose arising from cosmic radiation does not vary much according to latitude or time. The high levels result from the increase of the dose with altitude which is shown in figure 1. Therefore, people living at high altitudes above sea level or spending an appreciable fraction of their time flying aircrafts are exposed to significantly higher doses from cosmic rays than people living at or slightly above sea level.

a) Populations living at high altitude.

A number of cities are located at altitudes higher than 1 km above sea level. For example, the altitudes of Brasilia, Nairobi and Tehran are included between 1 and 2 km; those of México City and Quito are between 2 and 3 km while La Paz is at about 3.7 km above sea level.

Figure 2 shows the variation between sea level and 3 km of the air absorbed dose rate in air from cosmic-ray charged particles. At one, two, and three kilometres above sea level, the dose rates are 4.1, 6.2, and 9.8 μrad h^{-1}, respectively.

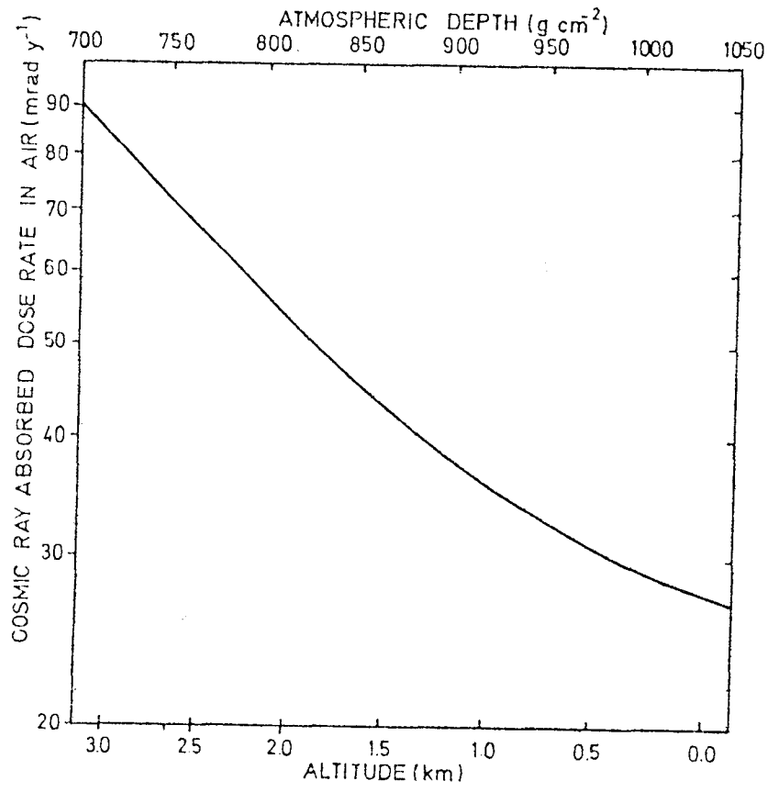

Fig. 2. Absorbed dose rates in free air from cosmic ray charged particles in the lower atmosphere at geomagnetic latitude 50°N. (Lowder and Beck, 1966)

b) Passengers using subsonic aircrafts.

In a conventional jet aircraft cruising at an altitude of 12 km, the tissue absorbed dose rate is about 0.3 mrad h^{-1} under average solar conditions. The resulting additional dose from cosmic radiation for people flying 100 h y^{-1} is thus about 30 mrad y^{-1}.

2. TERRESTRIAL RADIATION

No material on earth is completely free from the primordial radionuclides which have existed in the earth's crust throughout its history. In addition to cosmic rays, man has thus always been exposed to natural terrestrial radiation. The primordial radionuclides can be divided into those which decay directly to a stable nuclide (Table 2), and those belonging to the three radioactive series, headed by ^{238}U, ^{235}U, and ^{232}Th (figure 3).

TABLE 2

Some Non-Series Primordial Radio-Isotopes (UNSCEAR, 1972)

Radionuclide	Abundance in the lithosphere (ppm)	Half-life (years)	Alpha or maximum beta ray energy (keV)[a]	Gamma ray energies (keV)•
^{40}K	3	$1.3\ 10^{9}$	β 1,314 (89)	1,460 (11)
^{50}V	0.2	$6\ 10^{15}$	β ? (30)	783 (30), 1,550 (70)
^{87}Rb	75	$4.8\ 10^{10}$	β 274 (100)	
^{115}In	0.1	$6\ 10^{14}$	β 480 (100)	
^{138}La	0.01	$1.1\ 10^{11}$	β 210 (30)	810 (30), 1,426 (70)
^{147}Sm	1	$1.1\ 10^{11}$	α 2,230 (100)	
^{176}Lu	0.01	$2.2\ 10^{10}$	β 430 (100)	88 (15), 202 (85), 306 (95)

• Figures in parentheses indicate percentage yield per disintegration.

The primordial radionuclides of primary importance with respect to external gamma irradiation are ^{40}K and the radioactive series headed by ^{238}U and ^{232}Th. The decay of those natural radionuclides produces essentially alpha particles, electrons and electromagnetic radiation. Because the human organs and tissues to which the doses will be calculated for the purposes of this paper are shielded by at least a few millimetres of flesh which absorbs practically all of the energy of the alpha particles and electrons given off by the natural radionuclides, only the gamma exposure will be considered here.

The main contributors to the air absorbed dose in air are ^{208}Tl and ^{228}Ac in the ^{232}Th series, while in the ^{238}U series, about 99 per cent of the dose is due to ^{214}Pb and ^{214}Bi which are short-lived decay products of ^{222}Rn. The gamma rays that those nuclides give off range up to 2.6 MeV.

Man never escapes from terrestrial irradiation; he is outdoors exposed to the radioactivity of the rocks, the soil or the street pavement, while his exposure indoors is mainly due to the radioactivity content of the building materials.

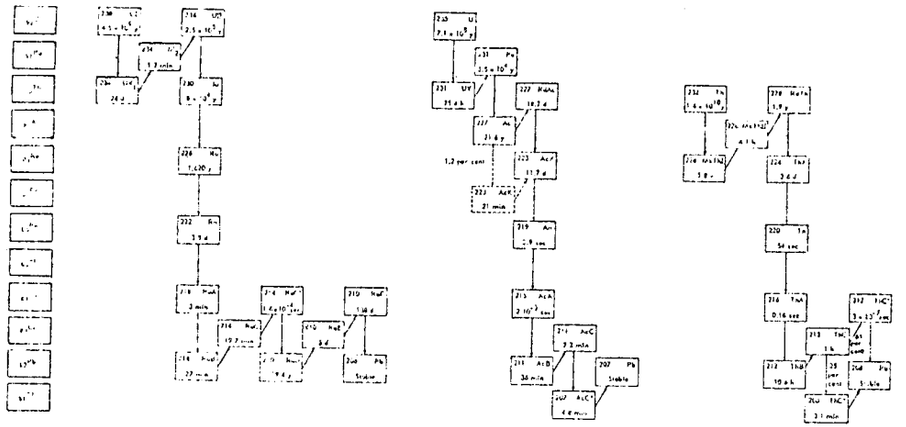

Fig. 3. Decay schemes of the natural series (boxes show atomic weight, historical name and half-life).

a) OUTDOOR EXPOSURE

The concentration of the primordial radionuclides in soil is determined by the radioactivity of the source rock and by the totality of subsequent soil-formation processes. In igneous rocks, the radioactivity is related to the quantity of silicates, being highest in acidic rocks and lowest in the ultrabasic rocks. Igneous rocks generally exhibit higher radioactivity than sedimentary rocks, while metamorphic rocks have concentrations typical of the rocks from which they are derived. However, certain sedimentary rocks, notably some shales and phosphate rocks, are highly radioactive (NCRP, 1974 b).

The radioactivity of soil, which is more directly relevant to the outdoors exposure, is that of the rock from which it is derived, diminished by the leaching action of moving water, diluted by increased porosity and by added water and organic matter, and increased by sorption and precipitation of radionuclides from incoming matter (NCRP, 1974a). An extensive study of the mean concentration of the natural radionuclides for soils of various genetic types of the Soviet Union (Kogan, 1971) shows that there is a regular trend for all the natural radionuclides which reflects the extent of biochemical reworking of the original soil-forming rocks (Table 3). In sod-podzolic, podzolic and boggy soils, where such processes as leaching, humification, and eluvial and alluvial transportation proceed at a vigorous state, the natural radioactivity is low. It is higher in forest and chernozem soils where the biochemical and geochemical processes are of a substantially lower intensity and it is equal to the corresponding values of the soil-forming rocks in arid climate soils (gray-brown soils and serozems).

Table 3 also presents an estimate of the average soil concentration on a worldwide basis and the dose rates for all the soils at 1 m above the ground level assuming that the radionuclides are distributed evenly (Beck et al., 1972).

TABLE 3

Average content of ^{40}K, ^{238}U and ^{232}Th in soils of various genetic types (Kogan, 1971; NCRP, 1974b) and corresponding air absorbed dose rates in air*.

Type of soil	Soil content (ppm)			Air absorbed dose rates in air (μrad h^{-1})			
	^{40}K	^{238}U	^{232}Th	^{40}K	^{238}U	^{232}Th	Total
Serozems	2.6	2.5	11.4	2.9	1.3	3.1	7.3
Gray-brown soils	2.7	2.2	9.6	3.0	1.2	2.6	6.8
Chestnut soils	2.2	2.1	9.5	2.4	1.1	2.6	6.1
Chernozems	1.7	1.7	8.8	1.9	0.9	2.4	5.2
Gray forest soils	1.4	1.4	6.5	1.5	0.7	1.8	4.0
Sod-podzolic soils	1.2	1.2	5.4	1.3	0.6	1.5	3.4
Podzolic soils	0.6	0.7	3.0	0.7	0.4	0.8	1.9
Boggy soils	0.4	0.5	1.5	0.4	0.3	0.4	1.1
World average	1.5	2.4**	6.0	1.7	1.3	1.6	4.6

* The relationships between the concentration in soil and the air absorbed dose rates in air at one meter above ground level are taken to be:
1.10, 0.54 and 0.27 μrad h^{-1} per ppm
of ^{40}K, ^{238}U and ^{232}Th, respectively (Beck et al., 1972).

** Inferred from the ^{226}Ra value assuming radioactive equilibrium with ^{238}U.

Results of large-scale surveys of outdoor terrestrial radiation. – In recent years, several surveys have been performed on a countrywide basis for the purpose of estimating the population exposure to natural radiation (Table 4).

The results are not altogether coherent as regards the quantity measured which is, in practice, the quantity for which the measuring device was calibrated. Some authors report exposure rates, others report absorbed air dose rates in air and others again tissue doses free in air. Unless the measuring and calibration conditions are well specified, these quantities are often somewhat ambiguous and intercomparisons between different investigations may be difficult.

The surveys were conducted using various methods and types of instrumentation. In the United States, aerial surveys were made in which an array of large NaI (Tl) crystals was flown in an aircraft at altitudes of 100 to 150m above the terrain (Burson, 1975). This method was also used in other large countries such as Canada (Richardson, 1975) and the Soviet Union (Kogan, 1971) but the results have not been used so far to estimate the average dose to the country's population.

Ground surveys were conducted in the other countries, listed in Table 4. Direct (or in situ) measurements were made in Switzerland, the Federal Republic of Germany, the German Democratic Republic, Italy and Poland, the detector being an ionization chamber in Switzerland, the German Democratic Republic and Italy, a gamma-spectrometer in Poland and a scintillation dosemeter especially developed for this purpose in the Federal Republic of Germany. In India, Japan and Taiwan, soil samples taken across the country were analyzed by gamma spectrometry in a laboratory.

TABLE 4

Estimate of the average external terrestrial dose to the population of several countries

Country	Average air absorbed dose rate in air (μrad h^{-1})	Number of measurements	Type of survey and instrumentation used	Reference
Federal Republic of Germany	5.2	> 20,000	Ground survey with scintillation dosemeters	Kolb, 1974
German Democratic Republic	9.1	1005	Ground survey with an ionization chamber and scintillation dosemeters	Ohlsen, 1971
India	3.6*	35 stations sampled	Analysis of soil samples by gamma spectrometry	Mishra and Sadasivan, 1971
Italy	7.2	1365	Ground survey with an ionization chamber	Cardinale *et al.*, 1975
Japan	4.1*	–	Analysis of soil samples gamma spectrometry	Yamagata and Iwashima, 1975
Poland	5.5	16 stations sampled	Ground survey with gamma spectrometers	Pensko, 1966
Switzerland	7.4	not indicated	Ground survey with an ionization chamber	Herbst, 1964
Taiwan	6.0*	26	Analysis of soil samples by gamma spectrometry	Weng *et al.*, 1975
United States	4.5	25 areas** covered	Aerial survey with gamma spectrometers	Oakley, 1972

* The air absorbed dose rates in air have been calculated from the average concentration of ^{40}K, ^{238}U (or ^{226}Ra) and ^{232}Th in soil using the conversion factors given in Table 3.

** Approximately 30 per cent of the country's population reside in the areas surveyed.

The average air absorbed dose rates in air indicated for each country in Table 4 are, in the case of Italy, Japan, Switzerland, the Federal Republic of Germany and the German Democratic Republic, population weighted (to the extent that the average values obtained in subdivisions of the country have been weighted according to their population); in the case of India and Poland, the figures indicated are reported averages while for Taiwan the average air absorbed dose rate in air has been calculated from the average concentration of surface soil in ^{40}K, ^{238}U and ^{232}Th.

Although the surveys did not take the variation with time into account and differed widely in the way they were conducted, in the type of instrumentation used and in the number of measurements, the average air absorbed dose rates obtained in air are all included within the relatively narrow range of 3.6 to 9.1 μrad h^{-1}.

The population-weighted average air absorbed dose rate in air for the countries listed in Table 4 is 4.3 μrad h^{-1}. The population involved is about 30 per cent of that of the world and, on that basis alone, this value could be considered to be representative of the world population exposure. The areas covered, however, represent only 2 per cent of the total land of the world and are all located in three separate regions of the Northern Hemisphere so that it could be argued that the rest of the world population might live in

areas where the air absorbed dose rate in air might be much higher or much lower than 4.3 μrad h^{-1}. However, the result based on the estimate of the worldwide average content of natural radionuclides is 4.6 μrad h^{-1} (see Table 3) and thus, in the absence of contradictory evidence, it is felt that 4.5 μrad h^{-1} is a reasonable estimate of the out-of-doors average air absorbed dose rate in air on a global basis.

Variability of the exposure – Considerations on the variability of the exposure around that mean value may be derived from some of the surveys listed in Table 4. Four of the countries provided the average doses for the populations of their administrative subdivisions: the 50 states and the capital district in the United States, the 11 Länder in the Federal Republic of Germany, the 20 regions in Italy and the 22 districts in Japan. The population of those subdivisions varies between 0.1 to 20 million people.

The population-weighted distribution of the air absorbed dose rate in air in the four countries is presented in Figures 4 (a) to 4 (d). A normal distribution fits reasonably well the histogram corresponding to the Federal Republic of Germany whereas the histograms for the other countries are less chracteristic. However, when the data for the four countries are combined (Fig. 5), they fit rather well a Gaussian distribution with the exception of the Italian regions of Lazio and Campania which represent 2.5 per cent of the population involved. The mean air absorbed dose rate for these four countries is 4.85 μrad h^{-1} with a standard deviation of 1.1 μrad h^{-1}. Assuming that the distribution holds on a global basis, 99 per cent of the world population residing in normal areas would live where the outdoor air absorbed dose rate in air from the primordial radionuclides falls between about 2 and 8 μ rad h^{-1}. However, it should be borne in mind that this applies only to dose rates averaged over population groups of at least 0.1 million people.

High exposure levels – It is clear from Figure 5 that there are regions in the world where the population is exposed to outdoor dose rates much higher than expected. The most famous are those located in India and Brazil.

In the coastal regions of the Indian State of Kerala, there is a stretch about 160 km long and 0.4 km wide characterized by patches of sand containing monazite with a high thorium content. About 70,000 people live in the 55 km long coastal strip which includes the most concentrated distribution of monazite (Gopal-Ayengar et al., 1972). The air absorbed dose rates ($\nu\beta + \gamma$) in air measured range up to 4,000 μrad h^{-1} (Gopal-Ayengar and Mistry, 1962).

Two types of high background regions have been found in Brazil: the monazite sand region along the Atlantic Coast and the zone of volcanic intrusives in the inland state of Minas Gerais.

The radiation levels in three towns (Guarapari, Meaipe and Cumuruxatiba) built over the monazite sands along the Atlantic Coast were surveyed in detail by Roser and Cullen (1964). Guarapari is a town of 5,000 people which receives an influx of about 10,000 vacationers every summer. In that town the air absorbed dose rates in air range from 100 to 200 μrad h^{-1} in the streets and up to 2,000 μrad h^{-1} in selected spots on the beach (Roser and Cullen, 1964; Penna-Franca et al., 1965). Meaipe is a fishing village of about 300 people where the average air absorbed dose rate in air is about 100 μrad h^{-1}. In Cumuruxatiba, the average level is 50 μrad h-^{1} (Roser and Cullen, 1964).

In the state of Minas Gerais, two eruptive regions have been intensively studied: Poços de Caldas and Araxá-Tapira. Near the city of Poços de Caldas stands a hill where air

absorbed dose rates in air of up to 2,800 μrad h^{-1} have been reported (Penna-Franca et al., 1965). However, this hill has a small area and is uninhabited. Araxá and Tapira are two towns located near volcanic intrusives where levels up to 400 μrad h^{-1} have been measured (Roser and Cullen, 1964).

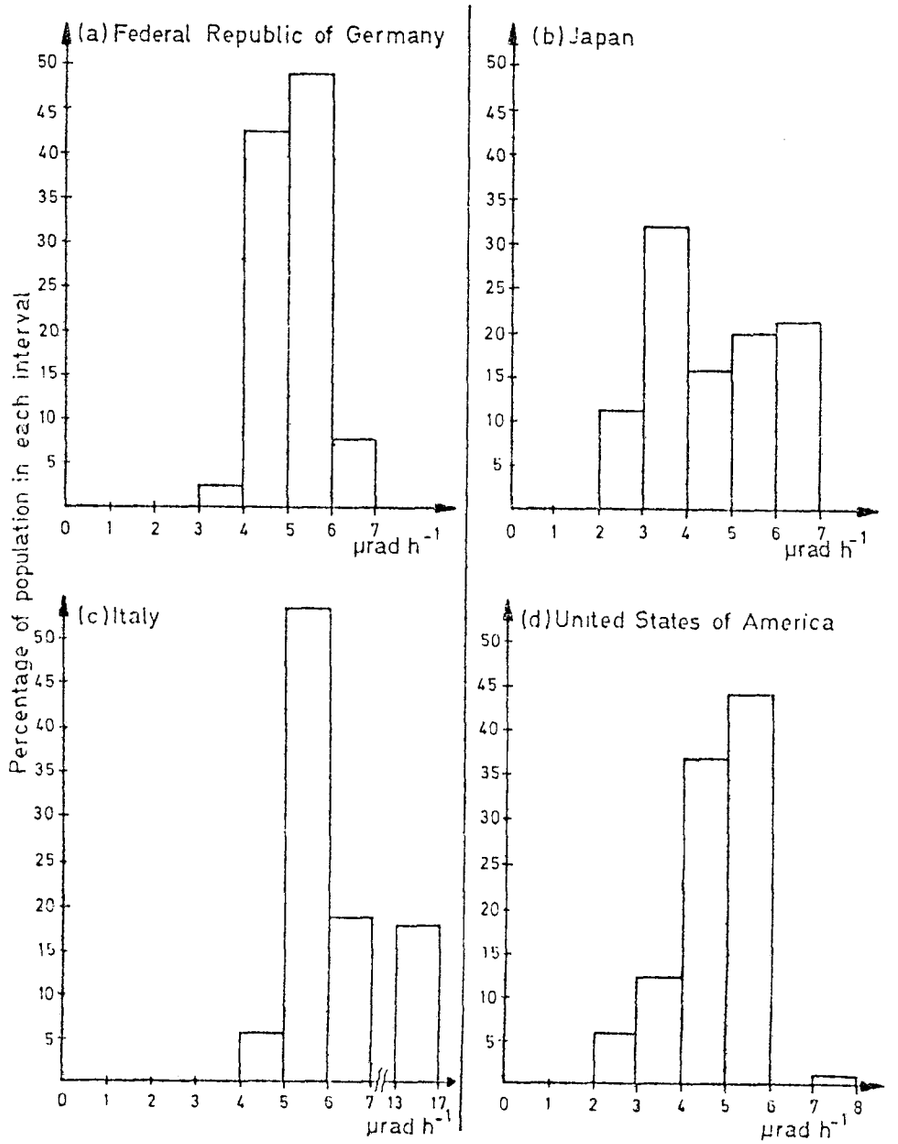

Fig. 4. Air absorbed dose rates in air in (a) the Federal Republic of Germany, (b) Japan, (c) Italy and (d) United States of America.

TABLE 5

Radioactive content of building materials

Type of building material	Country	Number of samples	Average activity concentration (pCi g^{-1}) ^{40}K	^{226}Ra	^{232}Th	Air dose rate* (μrad h^{-1})	Reference
Bricks, clinker	Fed. Rep. of Germany	–	17	2.2	2.6	25	Atom inf; Mehl, 1974
Clay bricks	United Kingdom	23	17	1.4	1.2	16	Hamilton, 1972
Red bricks	Soviet Union	55	20	1.5	1.0	16	Krisiuk, 1973
Bricks	Sweden	109	–	–	–	25	Hultqvist, 1956
Heavy concrete	Soviet Union	87	15	0.9	0.8	12	Krisiuk, 1973
Light concrete	Soviet Union	16	14	2.0	0.9	15	Krisiuk, 1973
Concrete	United Kingdom	5	14	2.0	0.8	15	Hamilton, 1972
Concrete without alum shale	Sweden	23	–	–	–	14	Hultqvist, 1956
Concrete containing alum shale	Sweden	29	–	–	–	130	Hultqvist, 1956
Cement	Fed. Rep. of Germany	–	<4	< 1.4	< 1.4	< 12	Mehl, 1974
Cement	Sweden	10	–	–	–	9	Hultqvist, 1956
Cement	Soviet Union	7	6	1.2	1.2	8	Krisiuk, 1973
Slagstone and sand	Fed. Rep. of Germany	–	9	2.2	2.8	24	Mehl, 1974
Natural sand and sand rejects	Soviet Union	32	7.1	0.63	0.5	7	Krisiuk, 1971, 1973
Natural plaster	United Kingdom	69	4	0.6	0.2	4	Hamilton, 1972
Natural plaster	Fed. Rep. of Germany	–	2.4	< 0.5	< 0.5	< 5	Mehl, 1974
Plaster	Soviet Union	1	10	0.25	0.17	5	Krisiuk, 1973
Chemical plaster	Fed. Rep. of Germany	–	<2	14	< 0.5	≅ 50	Mehl, 1974
Chemical plaster	United Kingdom	6	2	21	0.5	70	Hamilton, 1972
Granite	Soviet Union	2	40	3	4.5	46	Krisiuk, 1973
Granite bricks	United Kingdom	7	28	2.4	2.3	28	Hamilton, 1972
Tuff	Soviet Union	13	18	2.6	2.0	24	Krisiuk, 1973
Pumice stone	Fed. Rep. of Germany	–	24	2.2	2.3	26	Mehl, 1974
Slag pumice	Soviet Union	6	4.7	5.5	1.5	21	Krisiuk, 1973
Rock aggregate	United Kingdom	3	22	1.4	0.1	12	Hamilton, 1972
Lime	Sweden	4	–	–	–	2	Hultqvist, 1956
Phosphorus slags	Soviet Union	15	4	6.1	0.6	24	Krisiuk, 1971, 1973
Facing materials	Soviet Union	35	39	1.9	2.3	30	Krisiuk, 1973
Wood	Sweden	1	–	–	–	< 0.4	Hultqvist, 1956
Rock and silica wool	United Kingdom	2	negligible	negligible	negligible	negligible	Hamilton, 1972

* The air absorbed dose rate in air have been calculated assuming a 4 π geometry at an infinite thickness.

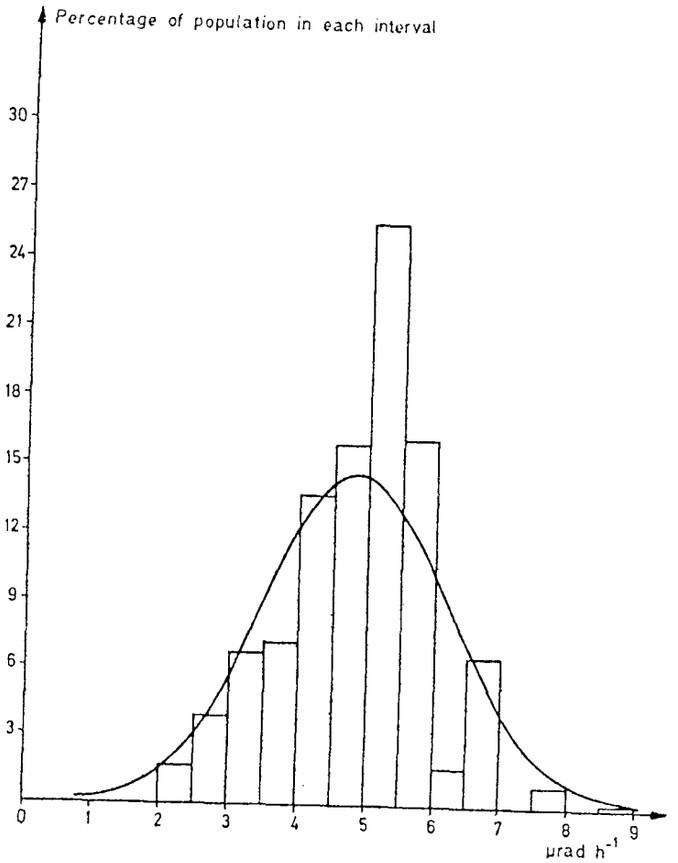

Fig. 5. Air absorbed dose rates in air: combined data from the Federal Republic of Germany, Japan, Italy, and the United States of America (the Italian region of Lazio and Campania have been excluded).

b) INDOOR EXPOSURE

Most individuals spend a large fraction of their time indoors where they are exposed to the irradiation arising from the radioactive content of the building materials. Table 5 presents the concentration of natural radionuclides in surveys conducted in the Federal Republic of Germany, Sweden, the Soviet Union and the United Kingdom. For a given type of commonly used building material, the range of concentrations is very wide; but the average values obtained in the four countries are reasonably close. Wood and materials used for thermal insulation are of a very low radioactive content, natural plaster and cement are also on the low side while granites, clay bricks and concrete are in the upper range.

The building materials act as both a source and a shield. The shielding effect is most clearly marked in wooden houses for which the source effect is small. Surveys conducted

in the United States (Lowder and Condon, 1965; Lindeken, 1971; Yeates, 1972) and in Australia (Yeates, 1973) have shown that the indoor dose on the ground floor of wooden houses is about 75 per cent of that measured outdoors. One floor upstairs, the doses are lower by a further 10 to 20 per cent (Yeates, 1972; Lindeken, 1971) For prefabricated houses, it has been determined in the study conducted in the Federal Republic of Germany that dose rates indoors are also lower than outdoors, the average reduction being 7 per cent (Kolb, 1974).

In the other types of houses, outdoor radiation is almost completely shielded by the walls. This has been demonstrated in various studies (see, for example, Ohlsen, 1971 and Yeates, 1972), in which it has been observed that the levels are about the same on various floors of a given masonry building. Therefore, in those dwellings, the indoor levels cannot be compared to those outdoors unless the building materials are of local origin. With equal content of radioactive substances in the bedrock of a given locality and in building materials, the dose rate might be expected to be twice as large indoors as outdoors as a result of the change from a 2π to a 4π geometry. However, correction coefficients should be applied allowing for the presence of windows and doors (Krisiuk, 1971). Reports on the direct determination of those correction coefficients have not been found in the literature.

A good estimate of the average indoors to outdoors dose ratio in masonry buildings will hopefully be obtained from the very extensive country-wide study from the Federal Republic of Germany in which 30,000 apartments were surveyed. From incomplete results (Kolb, 1974), it seems that the population-weighted average indoor dose is about 30 per cent higher than that outdoors (Table 6). Assuming that the number of prefabricated buildings is relatively small in the Federal Republic of Germany and that, on the average, the radioactive content of the building materials is about the same as that of the soils, roads and pavements around the building, the average ratio of the indoor to outdoor air absorbed dose rates in air for masonry buildings would be about 1.3. This figure is in reasonable agreement with the results of the United Kingdom study (Spiers, 1960), which was conducted on a much smaller scale. On the other hand, the corresponding value obtained in the German Democratic Republic (Ohlsen, 1971) is much smaller. However, this study, although it covered the whole country, involved only 700 dwellings and different types of instruments were used to measure the indoor and the outdoor air absorbed dose rates in air. Judging from the average outdoor doses for the Federal Republic of Germany and Poland (Table 4), it can be suspected that the average outdoor dose obtained in the German Democratic Republic is too high.

Estimate of the average indoor level of the absorbed air dose rate in air – Assuming that the proportion of wooden buildings (dwellings, offices, factories, shops, theatres, etc.) is about 20 per cent of the total and taking the average indoor to outdoor dose ratios to be 0.7 and 1.3 for wooden and masonry buildings, respectively, the average indoor air absorbed dose rate in air would be 18 per cent higher than that outdoors and the world population would be exposed to an average indoor air absorbed dose rate in air of about 5.3 μrad h^{-1}.

Variability of the absorbed air dose rate in air – Indications on the variability of the indoor doses in relation to the average may be derived from the survey conducted in the Federal Republic of Germany. As in the case of the outdoor air absorbed rate in air,

TABLE 6

Results of surveys of indoor terrestrial doses

Country	Number of measurements	Type of building	Indoors average air dose rate (μrad h^{-1})	Population weighted average dose (μrad h^{-1})	Indoors to Outdoors dose ratio	Population weighted indoors to outdoors dose ratio	Reference
Federal Republic of Germany	more than 20,000	solid	6.8	6.5	1.32	1.31	Kolb, 1974
		half-timber	6.6		1.20		
		prefabricated	4.3		0.93		
German* Democratic Republic	480 in old buildings 187 in new buildings	brick (old buildings)	7.2	7.4		0.78	Ohlsen, 1971
		brick (new buildings)	6.5				
		half-timber (old buildings)	7.6				
		stone (old buildings)	11.2				
		mixed construction (new buildings)	5.7				
		prefabricated (new buildings)	5.9				
Norway	823	wood	7.1				Storruste, 1965
	594	concrete	10.5				
	609	brick	11.9				
Poland	97	concrete	6.8		0.97		Pensko, 1966
Sweden	259	wood	5.1				Hultqvist, 1956
	365	brick	10.6				
	362	light-weight concrete containing alum shale	17.6				
United Kingdom	71	solid sedimentary rock (Dundee)	7.6		1.07		Spiers, 1960
	155	solid sedimentary rock (Edinburgh)	6.8		1.24		
	103	granite (Aberdeen)	9.7		0.82		
	172	granite (Aberdeenshire)	9.4		1.17		
United States	110	wood	3.9 (median value)		0.75		Lindeken, 1973 Lowder and Condon, 1965
	160	wood			0.7		

* The buildings are qualified as old if they were built before 1945; they are called new if they were built after 1945.

the population-weighted distribution seems to be normal; the mean value of the indoor dose would be 6.7 μrad h^{-1} and its standard deviation 1.0 μrad h^{-1} while the corresponding values for the outdoor dose would be 4.9 and 0.5 μrad h^{-1}, respectively. Assuming that these figures can be extrapolated to the global scale, it is tentatively estimated that 99 per cent of the world population is exposed to indoor doses, averaged over more than 0.1 million people, ranging from 2 to 9 μrad h^{-1}.

Tissue absorbed doses from terrestrial radiation – All the dose rates quoted so far for gamma radiation are air absorbed dose rates in air. They must be multiplied by the ratio of the mass absorption coefficient in tissue to that in air to convert them into tissue absorbed dose rates free in air. A value of s = 1.10 is correct within ± 1% for photon energies between 0.1 and 4 MeV.

The change from receptor-free conditions to a situation where a person is present in the radiation field will influence the field at the surface of the person. Backscattered radiation may increase the dose rate at the surface but the body will also act as a shield and reduce the dose rate. The influence of body shielding will depend upon the location of the organ of interest and the angular distribution of the radiation. The conversion factor g from the tissue absorbed dose rate free in air to the organ absorbed dose rate has been taken, for all organs, as 0.75 for external outdoor exposure (2π geometry) and as 0.63 for indoor exposure (3π geometry).

In order to calculate the annual tissue absorbed dose, the fraction of the year that a person spends out of doors has to be taken into account.

This proportion varies for different people depending on season, country, age, habits and type of work. For the purpose of this paper it will be assumed that the time spent out of doors is about 4-5 hours per day, i.e. the outdoor occupancy factor is 0.2.

Taking all those factors into account, the average tissue absorbed dose from terrestrial radiation for the world population is estimated at:

$$D = 4.5\ 10^{-1}\ (\text{nrad h}^{-1}) \times 1.1 \times 0.75 \times 8760 \times 0.2\ (\text{outdoor exposure})$$
$$+ 5.3\ 10^{-3}\ (\text{nrad h}^{-1}) \times 1.1 \times 0.63 \times 8760 \times 0.8\ (\text{indoor exposure})$$
$$= 5.9 + 25.7 = 31.6\ \text{mrad y}^{-1}$$

High levels of indoor exposure – Elevated levels may result from the use of highly radioactive building materials in normal areas or of local material in high-radiation areas.

a) Normal areas

The use of highly radioactive building materials may lead to elevated indoor radiation levels. Those building materials may be of natural origin, such as concrete containing alum shale in Sweden, pumice stone in the Federal Republic of Germany and in the Soviet Union, and granite wherever it is used (Table 5). They may also result from industrial processes, as is the case of chemical plaster in the Federal Republic of Germany and the United Kingdom, and tailing from uranium mills in the United Kingdom and the United States. As shown in the Swedish study (Hultqvist, 1956), the average doses in those buildings are much lower than what would be expected from the radioactive content of the material considered as the rest of building materials are usually less active.

b) High radiation areas

Information on the tissue absorbed doses received by the populations living in areas of high external terrestrial radiation in India and in Brazil have been attained in both countries by issuing personal thermoluminescent dosemeters to a fraction of the population. Gopal-Ayengar *et al.* (1972) carried out a dosimetric survey on a 55 km long coastal strip selected on the bases of high exposure rate, definable geographical boundaries and high population density. The average absorbed tissue dose rate for the 70.000 people residing in the region is estimated at 380 mrad y^{-1} on the basis of 8,513 individuals surveyed.

On the Brazilian coast, Cullen (1968) determined the average dose rate to a group of 317 inhabitants of Guarapari to be 550 mrad y^{-1} with a range of 90 to 2800 mrad y^{-1}.

INTERNAL IRRADIATION

Radioactive nuclides occurring in our natural environment enter the human body mainly through food and water, inhalation being of secondary importance, except for radon daughters. The dose rates to particular body organs are ideally derived from measured tissue concentrations, although an indirect estimation of the dose rates can be made from studies of the distribution of the radionuclides in the environment and in diet and from knowledge of their metabolic behaviour. Owing to the varying content of natural radioactive nuclides in the environment and in diet, the levels of radioactive intake, and therefore the corresponding concentrations in the human body, may vary from place to place for elements not subject to haemostasis. In a given location, time variation also occur as a result of changes in diet.

The natural radioactive nuclides have been classified into those that are being continually produced by the interactions of cosmic-ray particles with matter (or cosmogenic radionuclides), and those that were originally present at the formation of the earth (or primordial radionuclides), with their decay products.

1. COSMOGENIC RADIONUCLIDES

The most abundant cosmogenic radionuclide have been presented in Table 1. From the point of view of internal radiation doses, only ^{14}C is worth considering.

Carbon is one of the elements that is essential to all forms of life and thus is involved in most biological and geochemical processes on earth.

Carbon 14 is present in atmospheric carbon dioxide, in the terrestrial biosphere, and in the bicarbonates dissolved in the ocean. The specific activity of natural radiocarbon in the terrestrial biosphere, as measured in wood grown in the nineteenth century, is 6.13 ± 0.03 pCi $(gC)^{-1}$. As a first approximation, this value can be taken to be constant with time, as the variations in the production rate have only resulted in variations of a few per cent in wood samples in the past 6,000 years. However, during the past decades, it has experienced a slight decrease, of a few per cent as well, caused by the artificial combustion of ^{14}C – free fossil fuel (Suess effect).

The doses from natural ^{14}C are thus about the same for all the human population

groups of the world. Assuming that the specific activity of natural ^{14}C in the terrestrial biosphere is 6.1 pCi $(gC)^{-1}$ and that the carbon content in the human body is 12% in the soft tissues and 14% in bone, the annual doses are calculated to be 0.7 mrad to gonads, bone marrow and lungs, and 0.8 mrad to endosteal surfaces and small inclusions in bone. The decrease resulting from the Suess effect can be theoretically estimated at about 8% in 1975 (Baxter and Walton, 1970).

2. PRIMORDIAL RADIONUCLIDES

As indicated above, the primordial radionuclide can be classified into those which decay directly to a stable nuclide (Table 2) and those belonging to the three radioactive series, headed by ^{238}U, ^{235}U, and ^{232}Th (figure 3).

The only non-series radionuclides of significance are ^{40}K and ^{87}Rb, which have similar chemical properties.

a) POTASSIUM-40

Potassium-40, which is the major naturally occurring source of internal radiation dose to the whole body, enters the body mainly through foodstuffs. Potassium being like carbon an essential element, it is under close homeostatic control in the body and the dose rates from ^{40}K can be calculated from its isotopic abundance in the biosphere and the potassium content in human tissue.

The average potassium content of the whole body varies as a function of age and sex (figure 6). It is highest in adolescent males and lowest in elderly females, the ratio of the two values being about two. Taking a mean potassium content in tissues of 0.2 per cent and an isotopic ratio of ^{40}K of 0.0118 per cent, the dose rates from ^{40}K are estimated to be 19 mrad y^{-1} to soft tissues and 15 mrad y^{-1} to bone-lining cells and bone marrow.

b) RUBIDIUM-87

Very little is known about the behavior of rubidium in the human environment. The doses from ^{87}Rb, calculated from its isotopic abundance in the biosphere and the concentrations of rubidium in human tissues, are found to be 0.3 mrad y^{-1} to gonads and lungs and 0.6 mrad y^{-1} to bone surfaces and bone marrow.

c) URANIUM AND THORIUM SERIES

^{238}U and ^{232}Th each head a series of more than ten nuclides which get separated through physical, chemical, or biological means and therefore are not in equilibrium between them in air, water, food, and man. However, the two series can be classified in sub-series in which the activity of the precursor controls to a large degree the activity of the decay products. For the ^{238}U series: (a) ^{238}U, two short-lived nuclides and ^{234}U: (b) ^{226}Ra, which is frequently separated from its precursor, ^{230}Th, of no dosimetric significance in natural background, and from its decay product, ^{222}Rn, which is an isotope of a noble gas; (c) ^{222}Rn and its short-lived decay products (through ^{214}Po). This

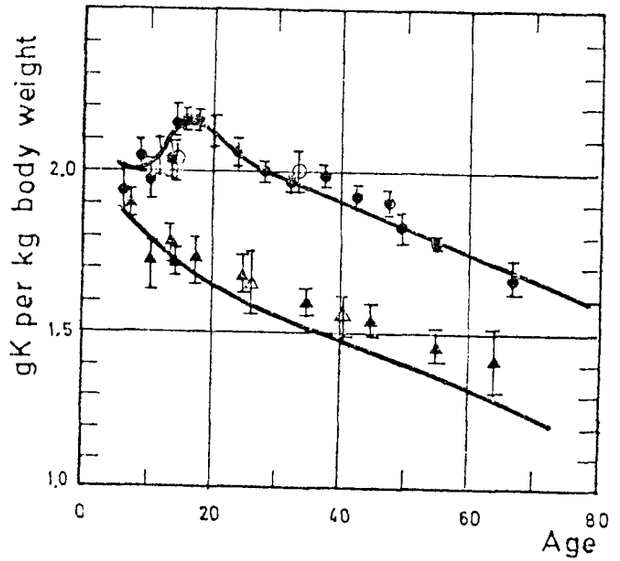

Fig. 6. Potassium concentration in the human body. The upper curve and circles refer to men, the lower curve and triangles to women. The curves represent the results of 10,000 measurements (Oberhausen and Onstead, 1965) the solid circles and triangles 802 determinations (Anderson, 1965) while the open circles and triangles are the results of measurements performed on 57 subjects (Bengtsson, 1967).

sub-series, important from the point of view of external radiation because of the highly energetic gamma rays emitted through decay of ^{214}Bi, is also important from the point of view of internal radiation; (d) the longlived ^{222}Rn decay products: ^{210}Pb, ^{210}Bi and ^{210}Po.

The ^{232}Th series has also been classified in three sub-series: (a) ^{232}Th by itself; (b) the sequence ^{228}Ra, ^{228}Ac, ^{228}Th and ^{224}Ra; (c) ^{220}Rn and its decay products. Because of their similarities, ^{226}Ra and the sequence headed by ^{228}Ra will be treated in the same section and ^{220}Rn and its decay products will be considered with ^{222}Rn. The decay chain of ^{235}U is not of dosimetric significance and will not be dealt with here.

(i) URANIUM

In this paper, uranium is assumed to consist of ^{238}U in radioactive equilibrium with ^{234}Th, ^{234}Pa and ^{234}U. One gramme of uranium contains 0.33 μCi of each of the four radionuclides.

There is little information of the dietary intake of uranium, but there is no doubt that it is much higher than that from inhalation. Values of 1 μg d^{-1} seem to be typical although a level of 30 μg d^{-1} has been reported for one area of the Soviet Union.

In man, the concentrations of uranium range from 0.1 to 0.9 nanogramme per gramme of wet soft tissue, compared to 20–30 nanogrammes per gramme of bone ash.

The corresponding dose rates to bone, calculated by the method of Spiers (1968) are 0.3 mrad y^{-1} to the bone-lining cells and 0.06 mrad y^{-1} to the whole marrow; in the calculations, however, uranium was assumed to be uniformly distributed in the 5000 g of mineral bone, or 2700 g of ash, although that may not be the case. If the conservative assumption that uranium deposits and stays on the trabecular surfaces were used, the calculated doses would be about 50 times higher for the bone-lining cells and about 30 times higher for the whole marrow (IAEA, 1971).

(ii) THORIUM-232

From a dust loading of 100 μg m^{-3} and a ^{232}Th concentration in soil of 6 ppm (Table 3), the intake through inhalation is about 1 fCi d^{-1}. There is no direct information on the dietary intake of ^{232}Th but an indirect estimate of about 0.1 pCi d^{-1} has been proposed (NCRP, 1974a). The contribution of this route to the body content is probably negligible because of the very low absorption of thorium through the gastro-intestinal tract.

Measured levels in rib bone show a linear increase with age (Lucas et al., 1970). The average value for an adult population would be about 1 fCi (g ash)$^{-1}$ which is about ten times less than the levels obtained for ^{238}U. However, thorium is known to deposit on the endosteum and the dose rates per unit activity of thorium in bone are much higher than those for uranium if it is assumed that the latter element is uniformly deposited in the total mass of the bone. The fragmentary information on levels and doses from ^{238}U and ^{232}Th is summarized in Table 7.

TABLE 7

Intakes, levels and doses from ^{238}U and ^{232}Th

		^{238}U	^{232}Th
Daily intake:	inhalation	5 ng	1 fCi
	diet	1 μg	0.1 pCi
Levels:	bone	20 – 30 ng (g ash)$^{-1}$	1 fCi (g ash)$^{-1}$
	soft tissues	0.1 – 0.9 ng g^{-1}	"
Tissue absorbed doses:	gonads	0.03 mrad y^{-1}	–
	lungs	0.03 mrad y^{-1}	–
	bone marrow	0.06 mrad y^{-1}	0.08 mrad y^{-1}
	bone-lining cells	0.3 mrad y^{-1}	0.5 mrad y^{-1}

(iii) RADIUM

(a) Human intake

Food consumption is in general the most important source of radium intake. The average dietary intake of ^{226}Ra and ^{228}Ra in areas of normal radiation background is about 1 pCi d^{-1} (UNSCEAR, 1972). Typical ^{226}Ra levels in most components of the diet range from 0.1 to 1 pCi kg^{-1} but some individual foods such as Brazil nuts or Pacific salmon contain much larger amounts of ^{226}Ra.

The contribution of water to the total intake is in general small when the drinking-water supplies are drawn from surface waters. However, ^{226}Ra levels of 1 to 10 pCi l^{-1} are not exceptional in well and mineral waters (Snihs, 1973; Kahlos, 1973; Allegrini, 1975; Remy, 1968). Available information on the concentrations of ^{228}Ra in those waters is limited but it seems that they are an order of magnitude lower (Kahlos, 1973).

The most famous populated areas in the world with abnormally high concentrations of thorium and uranium in their soil are located along the coast of Kerala in India and in the Araxá-Tapira region in Brazil.

The estimated *per caput* intakes of ^{226}Ra and ^{228}Ra of the Indian population along the Kerala coast are 3 and 160 pCi d^{-1}, respectively (UNSCEAR, 1972). 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 are ingesting alpha emitters at a level 5 times or more than that of a similar group living in Rio de Janeiro. Their intake of radium ranged from 10 to 40 pCi d^{-1} of ^{226}Ra and from 60 to 240 pCi d^{-1} of ^{228}Ra (UNSCEAR, 1972).

(b) Distribution in man and dose rates

When radium is taken into the body, it behaves chemically like calcium, and an appreciable fraction is deposited on bone surfaces and in areas of active bone turnover. In cortical bone the initial surface deposit gradually migrates to produce a diffuse distribution throughout the entire bone mineral (Evans, 1974). About 80–85 per cent of radium is thus contained in the skeleton, the remaining fraction being distributed approximately uniformly in soft tissues. In the areas of normal intake, the ^{226}Ra skeletal concentrations in man range from 4 to 40 fCi (g ash)$^{-1}$ (UNSCEAR, 1972) with an arithmetic average of 14 fCi (g ash)$^{-1}$ or about 40 picocuries per skeleton.

The ^{228}Ra levels in man might be expected to be lower than those of ^{226}Ra because of the shorter half-life of the former and the estimated biological half-life of radium in the body of 15–30 years. Thus, the build-up of ^{228}Ra would depend upon the age of the subject and it would be limited by its physical half-life to a maximum of about 50 per cent of that of ^{226}Ra (NCRP, 1974a). In fact, the average ratio between activites of ^{228}Th and ^{226}Ra in bone ash was found to vary between 0.25 and 0.5 which, if radioactive equilibrium between ^{228}Ra and ^{228}Th in bone is assumed, leads to an estimated upper limit of skeletal burden of 20 picocuries of ^{228}Ra in normal areas (UNSCEAR, 1972).

The dose rates to bone-lining cells and bone marrow presented in Table 8 have been calculated using the same assumptions as in the 1972 report, that is, (a) an average retention factor in the skeleton as well as in the soft tissues of 0.33 for ^{222}Rn and of 1.0 for ^{220}Rn, and (b) a uniform concentration of radium and its decay products over the total mass of mineral bone. In fact, with respect to ^{228}Ra and its decay products, it is known that a fraction of ^{228}Th, which is the long-lived alpha-emitter of the sequence, migrates to the endosteum (Butler et al., 1970). Therefore, the doses from that sequence to bone tissues are somewhat higher than indicated in Table 8.

Data on the skeletal burden of the populations living in the high external-radiation areas of India and Brazil are very scarce. In Brazil, the mean ^{226}Ra concentration of teeth of the population living in the Araxá-Tapira region has been estimated at 85 fCi (g ash)$^{-1}$

TABLE 8

Intakes, levels and doses from ^{226}Ra and ^{228}Ra

	^{226}Ra			^{228}Ra		
	Normal areas	Kerala, India	Araxá-Tapira, Brazil	Normal areas	Kerala, India	Araxá-Tapira, Brazil
Daily intake (pCi)	1	3	10 – 40*	1	160	60 – 240*
Reported levels in bone [fCi (g ash)$^{-1}$]	14	143	85	7	–	–
Tissue absorbed doses (mrad y^{-1}):						
Gonads	0.02	0.2	0.1	0.03	–	–
Lungs	0.02	0.2	0.1	0.03	–	–
Bone marrow	0.1	1.2	0.7	0.1	–	–
Bone-lining cells	0.6	6.6	3.9	0.8	–	–

* Range for the population group ingesting alpha emitters at a level 5 times or more than that of a similar group living in Rio de Janeiro.

which leads to a skeletal burden of about 230 pCi if it is assumed that the concentration in teeth is the same as that in bone. In India, the analysis of a femur bone yielded a ^{226}Ra concentration of 143 fCi (g ash)$^{-1}$ which corresponds to a skeletal burden of about 400 pCi (UNSCEAR, 1972).

(iv) RADON-222, RADON-220 AND THEIR SHORT-LIVED DECAY PRODUCTS

The exposure to the decay products of ^{222}Rn (radon) and ^{220}Rn (thoron) in air constitute the main component of the lung dose from natural sources.

Radon and thoron are exhaled from soil, water, building materials etc. and become dispersed in the air in the gaseous phase. The decay products, radon and thoron daughters, are produced in the solid phase as free atoms, usually as ions. Very soon, in the order of seconds to minutes, they become attached to aerosol particles in the air. The physical state of the activity incluences the deposition and subsequent fate of the inhaled activity in the respiratory system and consequently the dose.

1. Outdoor exposure

a) Atmospheric concentrations at ground level

The concentrations of radon and thoron in the air depend on the exhalation rate of radon and thoron from the soil, meteorological factors, geographical region and height of observation.

The radon concentration of continental air at ground level is of the order of 0.1 pCi l^{-1}, in coastal areas and islands 0.01 pCi l^{-1} and in areas of negligible exhalation rates such as oceans and arctic areas of the order of 0.001 pCi l^{-1} (UNSCEAR, 1972).

In continental air, the concentration of thoron at ground level is about the same as that of radon.

Radon and thoron daughters in air are very seldom in equilibrium with radon and thoron, respectively. The equilibrium factor F is defined as the ratio of the total potential alpha energy of the daughter concentrations to the total potential alpha energy of the daughters if they were in equilibrium with radon or thoron, respectively. The equilibrium factor F times the radon or thoron concentration is the concentration of radon or thoron for which the daughters in equilibrium would have the same potential alpha energy concentration as the atmosphere of interest. This equilibrium equivalent radon or thoron concentration (EER or EET) is expressed in the unit pCi l^{-1}.

The equilibrium factor F for radon has been considered by several authors directly of indirectly. The average values obtained varied between 0.4 and 0.8 while the extreme values were in the range 0.08 to 0.9.

In this paper, the average F – value for radon daughters in outdoor air is taken as 0.6 resulting in an average EER value of 0.06 pCi l^{-1} in continental air.

At ground level, the concentrations of the thoron daughters are in general one or two orders of magnitude lower than those of thoron. Direct measurements of the F – value for thoron daughters are not available. In continental air the measured concentrations of ^{212}Pb are on average 0.001 pCi l^{-1} (Blifford et al., 1956, Lockhart et al., 1966). This average is based on several long-term measurements (months to years). Assuming equilibrium between ^{212}Pb and ^{212}Bi the average EET value for continental air would be 0.001 pCi l^{-1}.

b) Doses

Inhalation of radon and thoron daughters results in an inhomogeneous internal irradiation of the respiratory tract primarily in the bronchial region near the hilus of the lung. The lung cancer among uranium miners predominantly appearing in the area of the large bronchi (Lundin et al., 1972) presumably originates in the basal cells in the basement membrane of the upper bronchial epithelium, which explains why the dose rate factor to those cells has been extensively studied, especially for mine air. Results of calculations by various authors using different models of the alpha dose to the basal cell layer of the critical bronchial region are in the wide range of 0.2 to 10 rad per working level month. A reasonable value for radon daughters would be one rad per working level month in normal mining conditions. It will be assumed in this paper that this value also applies in the case of exposure in outdoor air and in houses for either radon or thoron daughters. One rad per working level month corresponds to 60 μrad per pCi h l^{-1} (EER) and to 800 μrad per pCi h l^{-1} (EET).

Doses arising from exposure to radon daughters

Applying an outdoor occupancy factor of 0.2 and an EER value of 0.06 pCi l^{-1} leads to an annual dose to the basal cells of the basement membrane of the upper bronchial epithelium of about 5 mrad. The possible range is expected to be 1–25 mrad in different places and for different people.

The annual doses to the whole lung and to tissues and organs outside the respiratory system are much lower. They are estimated to be about one millirad to the whole lung 0.007 mrad to the gonads, and 0.008 mrad to bone marrow and to bone – lining cells.

Doses arising from exposure to thoron daughters

With an EET value of 0.001 pCi l^{-1} and an outdoor occupancy factor of 0.2, the dose to the basal cells of the upper bronchial epithelium is about 2 mrad y^{-1}. The corresponding dose to the whole lung is of the order of 0.1 mrad y^{-1} while the dose to the gonads would be 2 10^{-4} mrad y^{-1} and that to bone marrow and to bone – lining cells would be 3 10^{-3} mrad y^{-1}.

2. Indoor exposure

a) Radon daughters

The air concentration of ^{222}Rn and its daughters indoors depends upon the concentration in outside air, upon the ^{222}Rn emanation rate from the walls, and upon the ventilation rate in the room. Table 9 shows the results of measurements carried out in various countries.

^{222}Rn concentrations are usually higher indoors than outdoors; they are expected to be close to the values found outside if the rooms are efficiently ventilated, as in air-conditioned buildings, or if the emanation rate from the walls and the floor is low, as may be the case in wooden houses. High concentrations are found in rooms with very poor ventilation, for example in some basements, where the ^{222}Rn level will be proportional to the emanation rate from the walls, which in turn varies according to such parameters as the origin, nature, and porosity of the building material, and the type of paint or covering layer. Between those extremes, average concentrations several times higher than those recorded outside are observed in naturally-ventilated brick, aggregate, or concrete buildings, the measured level being sensitive to the actual degree of ventilation, which is connected to the individual habits of the inhabitants, and to the emanation rate from the walls.

It will be tentatively assumed in this paper that a representative values of the average ^{222}Rn concentration indoors is 1 pCi l^{-1}.

The degree of equilibrium of the ^{222}Rn decay products indoors is expected to be ruled by the ventilation rate, the equilibrium being nearly reached in rooms with poor ventilation, and highly perturbed in efficiently ventilated buildings. In naturally-ventilated rooms, the equilibrium conditions should be about the same as outside. The F – value is here taken as 0.5.

Using an indoor occupancy factor of 0.8 and a dose-rate factor of 60 μrad h^{-1} per pCi l^{-1}, the absorbed dose rate indoors can be roughly estimated to be 30 μrad h^{-1} which leads to an annual dose to the basal cells of the bronchial epithelium of about 200 mrad. The dose to the whole lung would be around 40 mrad y^{-1} while those to the gonads, the bone marrow and the bone-lining cells would be of the order of 0.3 mrad y^{-1}.

Other, usually minor, contributions to indoor exposure, include the use of natural gas in kitchen ranges and space heaters, and the consumption of water. An average radon concentration of about 20 pCi l^{-1} was measured in natural gas distribution lines in the United States, resulting in estimated doses to the segmental bronchioles of 0.6 mrad y^{-1}

TABLE 9

^{222}Rn concentration in dwellings (UNSCEAR, 1972)

Location	Number of buildings investigated	Type of building and building material	^{222}Rn concentration outdoors (pCi l^{-1})		^{222}Rn concentration indoors (pCi l^{-1})		Comments
			Range	Mean	Range	Mean	
Poland	28	Apartments – Concrete	0.06–0.16	0.11	0.14–2.14	0.44	Measurements made under similar conditions of ventilation
	8	Aggregate	0.06–0.09	0.08	0.26–1.10	0.35	
	6	Brick			0.08–0.37	0.19	
Sweden	55	Houses – Wood			0.3–0.9	0.54	Four air changes per hour
	87	Brick			0.3–2.1	0.91	
	83	Concrete (including alum shale)			0.3–4.5	1.86	
Union of Soviet Socialist Republics		Silicate brick			0.12–4.3		
		Red brick			0.19–1.10		
		Concrete			0.4		
		Adobe			0.3–10.0		
		Slag			4.0–8.0		
United Kingdom	1	House		0.04	0.06–0.31	0.16	Adequately ventilated
	1	House		0.13	0.2–0.7	0.4	Inadequately ventilated
	6	Industrial premises	0.04–0.19	0.09	0.005–1.2	0.3	Poor ventilation
	4	Office buildings		0.04	0.06–0.35	0.17	Air conditioned
United States of America: Boston area	7	One-family houses:	0.01–0.15	0.05			Number of air changes per hour: one to three in the basement, two to six on the first floor
		first floor (wood frame)			0.005–0.23	0.07	
		basement (concrete)			0.1–0.94	0.40	
	3	Apartments-Brick			0.01–0.19	0.09	Number of air changes per hour: five to nine
	4	Offices and laboratories			0.02–0.10	0.05	Number of air changes per hour: five to twelve. Air conditioned buildings
Tennessee	15	Houses – most of them of concrete construction					The ventilation rate was probably higher in Florida than in Tennessee as the outdoors temperatures were respectively, 23°C and 0°C
Florida	16				0.13–4.8 *	1.40	
					0.03–3.6 *	1.26	
New-York				0.13		0.25	

* Converted from working level units by assuming that ^{222}Rn and its daughters are in the equilibrium ratio 1/0.9/0.6/0.4.

TABLE 10

Estimated average tissue absorbed doses arising from inhalation of ^{222}Rn and ^{220}Rn short-lived decay products *

Source	Assumed EER or EET concentration (pCi l^{-1})	Tissue absorbed doses (mrad y^{-1})				
		Tracheo-bronchial tree	Lung	Gonads	Bone marrow	Bone-lining cells
^{222}Rn short-lived decay products						
1. Outdoor exposure	0.06	5 (1 – 25)	1 (0.2 – 5)	0.007 (0.001 – 0.03)	0.008 (0.002 – 0.04)	0.008 (0.002 – 0.04)
2. Indoor exposure						
a. building materials	0.5 (0.05 – 5)	200 (20 – 2000)	40 (4 – 400)	0.2 (0.02 – 2)	0.3 (0.03 – 3)	0.3 (0.03 – 3)
b. natural gas	0.0015 ($5\ 10^{-4}$ – $3\ 10^{-3}$)	0.6 (0.2 – 1)	0.1 (0.03 – 0.2)	$7\ 10^{-4}$ ($2\ 10^{-4}$ – 10^{-3})	$8\ 10^{-4}$ ($3\ 10^{-4}$ – $2\ 10^{-3}$)	$8\ 10^{-4}$ ($3\ 10^{-4}$ – $2\ 10^{-3}$)
c. water	(10^{-4} – 1)	(0.04 – 400)	(0.007 – 70)	($5\ 10^{-5}$ – 0.5)	($5\ 10^{-5}$ – 0.5)	($5\ 10^{-5}$ – 0.5)
^{220}Rn decay products						
1. Outdoor exposure	0.001	2	0.1	$2\ 10^{-4}$	0.003	0.003
2. Indoor exposure: building materials	0.01 (0.001 – 0.06)	60 (6 – 400)	5 (0.5 – 30)	0.008 ($8\ 10^{-4}$ – 0.05)	0.1 (0.01 – 0.6)	0.1 (0.01 – 0.6)

* The expected ranges, excluding extreme values, of the concentrations or of the doses, are given within parentheses.

from kitchen ranges and 2 mrad y^{-1} from space heaters. On the other hand, consumption of water containing 1 nCi l^{-1} of radon would lead to a dose from inhalation of about 30 mrad y^{-1} to the segmental bronchioles. It is worth mentioning that in addition small doses would be delivered as a result of ingestion. Assuming a daily consumption of 0.3 l, the annual dose to the stomach would be about 2 mrad while the dose to the whole body would be 0.02 mrad.

b) Thoron daughters

Published data on the concentrations of thoron decay products in buildings are limited. Harley and Pasternack (1973) reported average levels of 3.6 10^{-3} pCi l^{-1} of ^{212}Pb and of 2.7 10^{-3} pCi l^{-1} of ^{212}Bi in a laboratory in New York. In Salzburg, Steinhausler *et al.* (1975) found a mean ^{212}Pb concentration of 24 10^{-3} pCi l^{-1}, the extreme values being 0.1 10^{-3} and 62 10^{-3} pCi l^{-1}. Taking a typical ^{212}Pb value to be 10^{-2} pCi l^{-1} and assuming radioactive equilibrium between ^{212}Pb and ^{212}Bi, the absorbed dose rate to the basal cells of the terminal bronchioles is estimated to be 8 μrad h^{-1} corresponding to an annual dose of around 60 mrad. The dose to the whole lung would be about 5 mrad y^{-1} while those to the gonads, the bone marrow and the bone – lining cells would be 0.008, 0.1 and 0.1 mrad y^{-1}, respectively.

The various contributions to the dose arising from inhalation of radon and thoron decay products are summarized in Table 10.

(v) LONG-LIVED DECAY PRODUCTS OF ^{222}Rn: ^{210}Pb-^{210}Bi-^{210}Po

a) Intake by man

Inhalation. The concentrations of ^{210}Pb and ^{210}Po in surface air depend mainly on the rate of exhalation of ^{222}Rn from the ground and on the latitudinal distribution of land and sea areas. Consequently, they are highest in the temperate latitudes of the northern hemisphere. In those regions, the average concentrations of ^{210}Pb and ^{210}Po have been estimated at 14 fCi m^{-3} (Jaworowski, 1969) and 3.3 fCi m^{-3} (Parfenov, 1974). Assuming that a human being inhales 20 m^3 of air daily, the corresponding intakes are 0.3 and 0.07 pCi d^{-1}.

Since a cigarette contains about 0.6 pCi of ^{210}Pb and 0.4 pCi of ^{210}Po (Parfenov, 1974) and that both nuclides are volatile at the burning temperature of tobacco, cigarette smoking will lead to a substantial increase in the intake of ^{210}Pb and ^{210}Po through inhalation. For a person smoking a pack of 20 cigarettes a day, the values of the estimated intakes range from 0.12 to 2.1 pCi for ^{210}Pb and from 1.4 to 6.4 pCi for ^{210}Po (Parfenov, 1974). However, it should be pointed out that the conditions of inhalation while smoking are very different from those in normal respiration.

Ingestion. In normal areas, the values of the ^{210}Pb – ^{210}Po intake lie between one and ten picocuries per day, the contribution of drinking water to the total consumption being only a few per cent. As high levels are observed in the edible fraction of aquatic organisms, the intakes of ^{210}Pb and ^{210}Po in populations living mainly on seafood may thus be expected to be much higher than those of the populations with a "normal" diet.

This assumption is confirmed by the value of the ^{210}Pb intake in Japan (17 pCi d^{-1}).

A much better documented case of elevated intakes is that of the tens of thousands of reindeer and caribou breeders in the arctic and sub-arctic regions of the northern hemisphere. Their main food is the meat of these animals which contains unusually high levels of ^{210}Po as they graze in the wintertime on lichens which accumulate and retain ^{210}Pb and ^{210}Po. Table 11 gives estimates of the daily intakes of those radionuclides by the populations living in reindeer or caribou meat. The ^{210}Pb intake is not much higher than that of the populations in "normal" areas but the ^{210}Po intake is about one order of magnitude higher, a typical value being 100 pCi d^{-1} (Parfenov, 1974).

TABLE 11

Intakes, levels and absorbed doses from the ^{210}Pb – ^{210}Po sub-series

		Non-smokers in areas of normal dietary intake	Smokers in areas of normal dietary intake	Reindeer or caribou breeders
Daily intake (pCi):	inhalation	0.3 (^{210}Pb) 0.07 (^{210}Po)	0.4 – 2.4 (^{210}Pb) 1.5 – 6.5 (^{210}Po)	–
	diet	1 – 10 (^{210}Pb and ^{210}Po)	1 – 10 (^{210}Pb and ^{210}Po)	4 – 40 (^{210}Pb) 30 – 300 (^{210}Po)
Average ^{210}Po levels (pCi kg^{-1}):	bone	40	60	200
	lungs	6	15	60
	gonads	6	15	60
Tissue absorbed doses:	gonads	0.6	0.9	6
	lungs*	0.6	1.5	6
	bone marrow	0.3	0.4	1.5
	bone-lining cells	1.5	2.2	7.5

* Estimates of the absorbed dose to basal layer of cells in the bronchial epithelium range from 12 to 3000 mrad y^{-1}.

b) Distribution in man

Lead, bismuth and polonium-210 being the final decay products in the ^{238}U series, they would be present in the human body even in the absence of direct intake. However, under normal conditions, the decay in the body of ^{226}Ra, of ^{222}Rn and of their short-lived products does not play a major role in the accumulation of ^{210}Pb and ^{210}Po in the organism.

Areas of normal intake. The skeleton contains at least 70 per cent of the body burden of ^{210}Pb and ^{210}Po. An average value of ^{210}Po concentration in areas of normal intake is 37.5 pCi per kg of fresh bone with an ^{210}Po/^{210}Pb ratio of 0.7 leading to a ^{210}Pb concentration of 53.6 pCi kg^{-1} (Parfenov, 1974). Since ^{210}Po is not osteotropic, it is formed in the skeleton through decay of ^{210}Pb. The absence of equilibrium between ^{210}Po and ^{210}Pb is an indication that part of the ^{210}Po formed in the skeleton is not retained there, but is absorbed in the blood and deposited in other organs or excreted

from the body. It is estimated that the intake of ^{210}Po accounts only for one quarter of the ^{210}Po found in the body. The remaining three quarters are formed from ^{210}Pb accumulated over a long period of time in the skeleton (Parfenov, 1974).

Among the soft tissues, the highest ^{210}Po concentrations are about 15 pCi kg^{-1} in the liver and kidneys followed by the gonads and the lungs where the average values are about 6 pCi kg^{-1}. In all those tissues, the ^{210}Po/^{210}Pb activity concentration ratio is greater than one (Parfenov, 1974).

The total ^{210}Po content of the body is estimated to be of the order of 500 pCi in areas of normal intake. This corresponds to an average concentration of 7 pCi for kg of body weight.

The doses from the ^{210}Pb chain depend mainly on the highly energetic alpha particles of ^{210}Po. At equilibrium, the contribution from the beta emissions of ^{210}Pb and ^{210}Bi is only 7.5 per cent of that from ^{210}Po and will be neglected here. The doses to lungs and gonads are about 0.6 mrad y^{-1} and those to bone tissues calculated by the method of Spiers (1968) are found to be 1.5 mrad y^{-1} for bone lining cells and 0.3 mrad y^{-1} for the whole marrow. The average whole-body dose is about 0.7 mrad y^{-1}.

Differenees between smokers and no-smokers. Analyses of differences of ^{210}Po concentrations in smokers and non-smokers show that smoking does not increase the ^{210}Po levels in the human body by a factor of more than 1.5 except in the lungs where it is about 2.5. In view of the fact that the daily intake from smoking is at least 20 times the natural intake from atmospheric air, the ratio in the amounts contained in the lungs of smokers and non-smokers is relatively small. This strongly suggests that ^{210}Po inhaled during smoking is rapidly removed from the lungs (Parfenov, 1974).

Data on the degree of non-uniformity of ^{210}Po in the individual tissues of the lung are contradictory. One school of thought holds that ^{210}Po can be concentrated in the bronchial epithelium, particularly at points of bifurcation (Little *et al.*, 1965; Radford and Hunt, 1964), whereas the other considers that the levels in the bronchial epithelium do not exceed those in the alveolar region (Rajewsky and Stahlhofen, 1966; Hill, 1965). As a result, the estimates of the absorbed dose to the basal layer of cells of the bronchial epithelium range from 12 to 3000 mrad y^{-1} (Parfenov, 1974).

Reindeer or caribou breeders. Measurements carried out on the blood, placenta and bone tissue of inhabitants of the northern regions who consume caribou or reindeer meat regularly show levels higher than those in the populations of the temperate latitudes (Holtzman, 1966; Blanchard and Moore, 1970; Kauranen and Miettinen, 1969; Persson, 1975). By applying the tissue/placenta ratios derived by Hill (1966) for the "normal" populations, it can be estimated that the doses to soft tissues of reindeer herders are higher by a factor of 10 while the corresponding ratio is only 5 for bone tissues (Parfenov, 1974).

RECAPITULATION OF TISSUE ABSORBED DOSES IN "NORMAL" AREAS

Table 12 sumarizes the contribution of natural sources to the radiation exposure of human populations living in "normal" areas and under "normal" conditions. Much higher

TABLE 12

Tissue absorbed doses due to internal and external irradiation from natural sources in "normal" areas
The dose equivalents (mrem y^{-1}) are given within parentheses

Source of irradiation	Tissue absorbed doses (mrad y^{-1})											
	Gonads		Lung		Bone-lining cells		Bone marrow					
EXTERNAL IRRADIATION												
Cosmic rays: ionizing component	28	(28)	28	(28)	28	(28)	28	(28)				
neutron component	0.35	(2.1)	0.35	(2.1)	0.35	(2.1)	0.35	(2.1)				
Terrestrial radiation	32	(32)	32	(32)	32	(32)	32	(32)				
INTERNAL IRRADIATION												
Cosmogenic radionuclide: ^{14}C	0.7	(0.7)	0.7	(0.7)	0.8	(0.8)	0.7	(0.7)				
Primordial radionuclides:												
^{40}K	19	(19)	19	(19)	15	(15)	15	(15)				
^{87}Rb	0.3	(0.3)	0.3	(0.3)	0.6	(0.6)	0.6	(0.6)				
^{210}Pb – ^{210}Po	0.6	(6)	0.6	(6)	1.5	(15)	0.3	(3)				
^{220}Rn – ^{208}Tl	0.0002	(0.002)	5	(50)	0.003	(0.03	0.003	(0.03)				
^{222}Rn – ^{214}Po	0.2	(2)	40	(400)	0.3	(3)	0.3	(3)				
^{226}Ra	0.02	(0.2)	0.02	(0.2)	0.6	(6)	0.1	(1)				
^{228}Ra – ^{224}Ra	0.03	(0.3)	0.03	(0.3)	0.3	(3)	0.06	(0.6)				
^{238}U – ^{234}U	0.03	(0.3)	0.03	(0.3)	0.3	(3)	0.08	(0.8)				
^{232}Th	–	–	–	–	0.5	(5)	0.08	(0.8)				
Rounded total	81	(91)	129	(539)	80	(112)	78	(86)				

external doses are received by population groups living at high altitudes or in regions of high natural radioactivity.

In a similar way, a number of population groups are exposed to elevated internal absorbed doses. Such population groups are the caribou or reindeer breeders, or the people living in poorly ventilated concrete houses.

The four tissues considered in Table 12 are the gonads, the lungs, the bone marrow and the bone-lining cells. For comparison purposes, Table 12 also includes four tissues the estimates in terms of dose equivalent.

As a result of inhalation of ^{222}Rn and ^{220}Rn short-lived decay products, the dose to the entire lung is due for a substantial part to alpha particles and is more than 30 per cent higher than the doses to the three other tissues. It is worth mentioning that in addition to the doses included in Table 12 yearly doses of the order or 200 mrad are received by the basal epithelial cells of the tracheo-bronchial tree.

REFERENCES

ALLEGRINI, N., M. de BORTOLI, P. GAGLIONE *et alii.* Natural radioactivity levels in some drinking mineral water in Italy, and related doses to the population. Proceedings of the Second International Symposium on the Natural Radiation Environment (ADAMS, J. A. S., W. M. LOWDER and T. F. GESELL, eds) U.E.R.D.A. Report CONF 720805 (1975).

ANDERSON, E. C. Determination of body potasium by 4π gamma counting. Chapter 17 in radioactivity in Man. Second Symposium. (Meneely, G. R. and S. M. Linde, eds). Charles C. Thomas. Springfield, Ill., (1965).

Atom informationen 4/74. p. 18–20, The influence of building materials on the radiation exposure of the population (1974).

BECK, H. L. et al. U.S.A.E.C. report HASL 258 (1972).

BENGTSSON, L. G. Time variations of caesium 137 and potassium in humans from Southern Sweden. Acta Radiologica: Therapy Physics Biology 6: 259–282 (1967).

BLANCHARD, R. L. and J. B. MOORE, ^{210}Pb and ^{210}Po in tissues of some Alaskan residents as related to consumption of caribou or reindeer meat. *Health Phys.*, 18: 127–134 (1970).

BLIFFORD, J. H. Jr., J. H. FRIEDMAN, L. B. LOCKHART, Jr. and R. A. BAUS. Geographical and time distribution of radioactivity in the air. *J. Atmospheric and Terrestrial Physics*, 9: 1–17, (1956).

BURSON, Z. G., P. K. BOYNS and A. E. FRITZSCHE . Technical procedures for characterizing the terrestrial gamma radiation environment by aerial surveys, p. 559. Proceedings of the second international symposium on the natural radiation environment – August 7–11, 1972 Houston, Texas USA – U.S.E.R.D.A. Report Conf 72-0805 (1975).

BUTLER, G. C., N. T. GRIDGEMAN and R. S. Mc CULLOUGH, The dosimetry of alpha-emitting bone seekers. Presented at the Second International Congress of the International Radiation Protection Association. Brighton, England, May 3–8, 1970.

CARDINALE, A., G. CORTELLESSA, F. GERA et al., Distribution in the Italian population of the absorbed dose due to the natural background radiation. Proceedings of the Second International Symposium of the Natural Radiation Environment (ADAMS, J.A.S., W.M. LOWDER and T.F. GESELL, eds.). USAEC Symposium Series (1975).

CULLEN, T. L. Dosimetric measurements in Brazilian regions of high natural radioactivity, in Radiation Protection (Snyder, W. W., H. H. ABEE, L. K. BURTON et al., eds.) Pergamon Press, New York, (1968).

EVANS, R. D., Radium in man. *Health Phys.*, 27: 497–510 (1974).

GOPAL-AYENGAR, A. R. and K. B. MISTRY, On the radioactivity of plants from the high radiation areas of the Kerala Coast and adjoining regions. I. Studies on the uptake of gamma – emitting radionuclides. pp. 3–16 in. Radioisotopes in soil-plant nutrition studies. IAEA publication STI/PUB/55. Vienna (1962).

GOPAL-AYENGAR, A. R., K. SUNDARAM, K. B. MISTRY et al. Evaluation of the long-term effects of high background radiation on selected population groups of the Kerala coast. Vol. 11, P. 31–51 in Peaceful Uses of Atomic Energy. Proceedings of the Fourth International Conference, Geneva, 6–16 september 1971. Published by the United Nations and the International Atomic Energy Agency (1972).

HAMILTON, E. I., The relative radioactivity of building materials. *Amer. Ind. Hyg. Ass. J.*, 32: 398–403 (1972).

HARLEY, N. H. and B. S. PASTERNACK. Experimental absorption applied to lung dose from thoron daughters. *Health Phys.*, 24: 379–386, (1973).

HERBST, W. Investigations of environmental radiation and its variability, p. 781–796 in The Natural Radiation Environment University of Chicago Press, Chicago (1964).

HILL, C. R. Polonium-210 in man. *Nature*, 208: 423–428 (1965).

HILL, C. R. *Science*, 152: 1261 (1966).

HOLTZMAN, R. B. *Nature*, 210: 1054 (1966).

HULTQVIST, B. Studies on naturally occuring ionizing radiations. *Kgl. Svenska Vetenskaps. Handl.*, 6, Ser. 4, No. 3, 1956.

I.A.E.A. Manual on Radiation Haematology. A joint undertaking by IAEA and WHO, Technical reports series. 123, Vienna, 1971.

JAWOROWSKI, Z. Radioactive lead in the environment and in the human body. *At. En. Rev.*, 7: 3–45 (1969).

KAHLOS, H. and M. ASIKAINEN. Natural radioactivity of ground water in the Helsinki area. Report SFL-A19, Institute of Radiation Physics, Helsinki, 1973.

KAURANEN, P. and J. K. MIETTINEN, ^{210}Po and ^{210}Pb in the Arctic food chain and the natural radiation exposure of Lapps. *Health Phys.*, 16: 287–295 (1969).

KOGAN, R. M. Gamma Spectrometry of Natural Environments and Formations. IPST, Jerusalem, 1971.

KOLB, W, Die Strahlenbelastung der Berölkerung in Wohnhäusern-Zwischenbericht über ein BML – Vorhaben. Paper presented at a meeting on natural radiation in Helgoland (September 1974).

KRISIUK, E. M., et al. A study on radioactivity of building materials. Leningrad Research Institute for Radiation Hygiene, 1971.

KRISIUK, E. M., S. J. TARASOV et al., Exposures from radiation sources of natural origin in Proceedings of the Third International Congress of the International Radiation Protection Association. Washington, D. C., September 1973.

LINDEKEN, C. L., D. E. JONES and R. E. Mc MILLEN, Natural terrestrial background variations between residences. U.S.A.E.C. report UCRL-72964 (1971).

LINDEKEN C. L., D. E. JONES, R. E. Mc. MILLEN. Environmental radiation background variations between residences. *Health Physics*, 24: 81–86 (1973).

LITTLE, J. B. et al. *New Engl. J. Med.*, 273: 1343 (1965).

LOCKHART, L. B. Jr, R. L. PATTERSON, Jr. and A. W. SAUNDERS, Jr. Airborne radioactivity in Antarctica. *J. Geophys. Res.*, 71 (8): 1985-1991(1966).

LOWDER, W. M. and W. J. CONDON. Measurement of the exposure of human populations to environmental radiation. *Nature*, 206: 658–662 (1965).

LOWDER, W. M. and H. L. BECK, Cosmic ray ionization in the lower atmosphere. *J. Geophys. Res.*, 71: 4661–4668 (1966).

LUCAS, H. F., Jr., D. N. EDGINGTON and F. MARKUN, Natural thorium in human bone. *Health Phys.*, 18: 739–742 (1970).

LUNDIN, F. E. Jr., J. K. WAGONER, J. K. and V. E. ARCHER. Radon daughter exposure and respiratory cancer, quantitative and temporal aspects. Joint Monograph no. 1,1971. U. S. Dep. Of Health, Ed. and Welfare PHS.

MEHL, 1974. Personal communication.

MISHRA, U. C. and SADASIVAN. Natural radioactivity levels in India soils. *J. Scient. Ind. Res.*, 30: 50–62 (1971).

NCRP – Natural background radiation in the United States. Draft Report of Scientific Committee 43 – (1974a).

NCRP – Draft Report of Scientific Committee 35 (1974b).

OAKLEY, D. T. Natural radiation exposure in the United States. U. S. Environmental Protection Agency report ORP/SID 72-1, Washington D. C., 1972.

OBERHAUSEN, E. and C. O. ONSTEAD. Relationship of potassium content of man with age and sex. Results of 10,000 measurements of normal persons; factors influencing potassium content. Chapter 14 in Radioactivity in Man, Second Symposium (Meneely, G. R. and S. M. Linde, eds.). Charles C. Thomas, Springfield, Ill., 1965.

O'BRIEN, K. and J. E. Mc LAUGHLIN. Calculation of dose and dose-equivalent rates to man in the

atmosphere from galactic cosmic-rays. United States Atomic Energy Commission report HASL-228. New-York, 1970.
OHLSEN, H. Determination of the mean population burden from natural external radiation in the Soviet zone of Germany. Staatliche zentrale für Strahlenschutz, report No. SZS-14/69 also U.S.A.E.C. Translation report AEC-tr-7216 (1971).
PARFENOV, Y. D. Polonium-210 in the environment and in the human organism. *At. En. Rev.*, 12: 75–143 (1974).
PENNA-FRANCA, E., C. COSTA RIBEIRO, M. TEITAKOWSKI et al., Survey of radioactive content of food grown on Brazilian areas of high natural radioactivity. *Health Phys.*, 11: 1471–1484 (1965).
PENSKO, J. Dosimetry of environmental gamma radiation in Poland by means of gamma-ray spectra in the field. Report No. CLOR-48/D. Warsaw, 1966.
PENSKO, J. Environmental radiation measurements in Poland by means of scintillation methods, p. 499–519 in Actes du congrès international tenu à Toulouse les 14, 15, 16 mars 1967 sur la radioprotection du milieu devant le développement des utilisations pacifiques de l'énergie nucléaire. Société Française de Radioprotection, Paris, 1968.
PENSKO, J., K. MAMONT and T. WARDASZKO. Measurements of ionizing radiation inside blocks of flats in Poland. *Nukleonika*, 14 (4): 319–424 (1969).
PERSSON, B. R., Radiolead (^{210}Pb), Polonium (^{210}Po) and Stable Lead in the Food-chain Lichen, Reindeer and Man in Proceedings of the Second International Symposium on the Natural Radiation Environment (ADAMS, J.A.S., W.M. LOWDER and T. F. GESELL, eds.) USAEC Symposium Series, 1975.
RADFORD, E. P. and V. R. HUNT, *Science*, 143:3603 (1964).
RAJEWSKY, B. and W. STAHLHOFEN. *Nature*, 209: 1312 (1966).
REMY, M. L. et P. PELLERIN, Radioactivité naturelle de 250 sources hydrominérales françaises, Rapport SCPRI no 117 ou Bulletin de l'INSERMT 23: 23–62 (1968).
RICHARDSON, K. A., A. G. DARNLEY and B. W. CHARBONNEAU. Aiborne gamma-ray spectrometric measurements over the canadian shield, p. 681 in Proceedings of the second international symposium on the natural radiation environment – august 7-11, 1972 Houston, Texas USA – U.S.E.R.D.A. Report conf – 72-0805 (1975).
ROSER, F. X. and T. L. CULLEN, External radiation levels in high background regions of Brazil. Chapter 51 in the Natural Radiation Environment (ADAMS, J. A. S. and W.M. LOWDER, Eds.) The University of Chicago Press, 1964.
SNIHS, J. O. The content of some natural radioactive elements, especially ^{222}Rn, in some potable waters in Sweden. *Nordic Hydrol.*, 4: 256–274 (1973).
SPIERS, F. W., Gamma-ray dose-rate to human tissues from natural external sources in Great Britain, p. 66–72 in the Hazards to Man of Nuclear and Allied Radiation. A second report to the Medical Research Council. London, 1960.
SPIERS, F. W. Radioisotopes in the Human Body: Physical and Biological Aspects. Academic Press, New York and London (1968).
STEINHAUSLER, F., W. HOFMANN and E. POHL, Urban natural radioactivity in Salzburg, Austria, and its resulting dose for various organs in different groups of inhabitants. Paper G4 presented at the Third European Congress of the International Radiation Protection Association, Amsterdam, 13–16 May 1975.
STORRUSTE A., A. RTISTAD, T. RUDJORD et al. Measurement of environmental gamma radiation in Norwegian houses. *Health Phys.*, 11: 261–269 (1965).
UNSCEAR 1972. Ionizing radiation: Levels and Effects. Vol. I: Levels. United Nations Scientific Committee on the Effects of Atomic Radiation, 1972.
WENG, P. S., C. M. TSAI and T. C. CHU, Environmental radioactivity and radiation measurements in Taiwan, Republic of China. Proceedings of the Second International Symposium on the Natural Radiation environment (ADAMS, J.A.S., W.M. LOWDER and T.F. GESELL' eds.) USAEC Symposium Series, 1975.
YAMAGATA, N. and K. IWASHIMA, Terrestrial background radiation in Japan. *Health Phys.*, 13: 1145–1148 (1967).
YEATES, D. B., A. S. GOLDIN and D. W. MOELLER. Natural radiation in the urban environment. *Nuclear Safety*, 13: 275–286 (1972).
YEATES, D. B. and B. E. KING. Estimation of the gamma-ray natural background radiation dose to an urban population in Western Australia *Health Phys.*, 25: 373–379 (1973).