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NOTE

Throughout this report and its annexes cross-references are denoted by a letter followed by a number: the letter refers to the relevant technical annex (see Table of Contents) and the number is that of the relevant paragraph. Within each technical annex, references are made to its individual scientific bibliography by a number without any preceding letter.

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ANNEXES

Annex B
RADIATION FROM NATURAL SOURCES

TABLE OF CONTENTS

1. A distinguishing characteristic of irradiation by natural sources is that the entire population of the world is exposed to it and that it remains relatively constant in time, while varying from place to place with local geological conditions. The various natural sources include:

(*a*) External sources of extra-terrestrial origin (cosmic rays) and external sources of terrestrial origin, i.e. the radioactive isotopes present in the crust of the earth and in air.

(*b*) Internal sources, i.e. the radioisotopes K^{40} and C^{14} which exist as a small percentage of these elements and are normal constituents of the body, and other isotopes such as Ra^{226}, Th^{232} and their decay products that are taken up from the environment.

I. COSMIC RAYS

2. The primary component of cosmic rays is the radiation incident upon the top of the atmosphere of the earth. It is composed of 79 per cent (in number) of protons, 20 per cent of alpha particles, 0.78 per cent of C, N, O nuclei and 0.22 per cent of nuclei with $Z > 10$.[1]* The energy of the primary particles is very high and values up to 10^{19} eV have been reported.

Absorption in air

3. The primary particles lose energy in their passage through matter by ionization, radiation, and nuclear interactions and thus produce new groups of rays. This secondary radiation, still very energetic, is composed of electrons, photons, neutrons and mesons. The composition of the radiation changes with altitude.

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4. The radiation at sea level is composed of mesons (~80 per cent) which constitute the secondary hard component, electrons (~20 per cent), which constitute the secondary soft component, and some primary protons (~0.05 per cent)[2]. The average mass absorption coefficient of the soft component at sea level has been reported to be 8.5×10^{-3} cm²/g (E. Regener, quoted by Hess[3]).

Variations

5. The intensity of cosmic rays increases very strongly with altitude in consequence of decreased atmospheric absorption, and increases with increasing geomagnetic latitude in consequence of the effect of the earth's magnetic field. The latitude effect is confined to latitudes between 0° and approximately 55° (apparently at all altitudes). Small, short-lived changes of intensity in time are produced by solar flares (up to 12 per cent)[4,5]. Temperature changes in the upper layers of the atmosphere, local increases in pressure, air fronts and other factors also produce negligible temporary variations in intensity, but they are not significant from the point of view of the external irradiation of the organism.

6. Different authors give different values for cosmic ray intensities at sea level (table I) even at comparable latitudes. There are indications[6,7] that the most reliable figure for the intensity at the middle latitudes (~50°) and at sea level is 1.9 – 1.96 ion-pairs/cm³·sec, which gives a soft tissue and gonad dose of ≈ 28 mrad/year.

TABLE I. INTENSITY OF COSMIC RAYS AND DOSES TO THE SOFT TISSUES AND GONADS IN VARIOUS REGIONS NEAR SEA LEVEL

Place of observation	*Geomagnetic latitude in degrees*	*Ionization in ion pairs per cm³·sec*	*Dose to the soft tissues and gonads in mrad/year*	*Ref.*
Great Britain...	55° N	1.92	28	8
United States...	41° N	1.96	29	6
Austria[a].....	48° N	1.9	28	9
France.....	49° N	1.66 {Hard 1.15 / Soft 0.51}	24	10
Japan.....	25° N	2.35 {Hard 1.76 / Soft 0.59}	34	11
Argentina[a].....	23° 15′ S	1.4	20	12
	52° 42′ S	1.9	28	

[a] Measured by counters.

Variation with altitude

7. The ionization in ion pairs/cm³·sec and corresponding dose rates in air at NTP are given in table II for certain locations. The table shows that an increase in altitude from 0 m to 3,000 m gives an approximately threefold increase in intensity, while the latitude variation even at 3,000 m is only 50 per cent. Neher's data for sea level intensity, on which table II is based, are 30 per cent higher than those of other observers. Therefore, the values given in this table may be considered as upper limits.

TABLE II.[13] COSMIC RAY INTENSITIES AND DOSE RATES

Altitude m	*Intensity ion pairs/cm³·sec*		*Dose rate mrad/year*	
	At 50° latitude	*Near Equator*	*At 50° latitude*	*Near Equator*
0.....	2.8	2.4	41	35
1500.....	4.5	3.0	66	44
3050.....	8.8	6.1	128	89
4580.....	18	12	263	175
6100.....	34	23	500	340

II. PROPERTIES OF NATURAL RADIOACTIVE ISOTOPES

8. Naturally occurring radioactive isotopes such as H^3, C^{14}, K^{40}, Rb^{87}, Th^{232} and U^{238} and the decay products of the last two isotopes are widely distributed in rocks and soils and in the air. Physical characteristics of some isotopes are given in tables IIIa and IIIb. The data given in these tables may be found in many textbooks, but they are included here because they illustrate the relative importance of different radioactive elements and are used in calculations later on. The dose rate for an element at given concentration is determined from decay, yield and energy of its radiation. Shielding factors are assessed in the light of the penetrating power of the radiation. The relative contribution of the decay products of radium and thorium to total doses can be calculated, and the deviation from the theoretical equilibrium concentration of the decay products of radium in bones, caused by partial diffusion of radon, can be taken into account.

9. Some of the isotopes listed in the tables viz. K^{40}, Th^{232}, U^{238}, have half-lives comparable to the geological age of the earth, estimated at 4×10^9 years, and for this reason are still present in nature. Other isotopes, in spite of their short half-lives, are also present today, because they are decay products of long-lived isotopes like Ra^{226}, or because they are produced from atmospheric nuclei by cosmic rays, like C^{14} and H^3.

III. NATURAL RADIOACTIVE ISOTOPES IN THE ENVIRONMENT

Uranium and Thorium

10. Naturally radioactive elements are widely distributed over the earth's surface. Thorium-bearing minerals are found in the United States (Rocky Mountains area and the Carolinas), in India (Kerala coast), in Brazil (coastal region of Espirito Santo), on Taiwan and in other parts of the world. Uranium has been found in large quantities in the United States (in brown coal deposits, petroleum beds, and the phosphatic rocks of Florida), the Belgian Congo, Ontario and Saskatchewan in Canada, Fergana in the USSR, Czechoslovakia and South Africa and other areas. For fuller information on the distribution of uranium aid thorium, see Kerr.[15]

11. Radioactive elements are more commonly associated with certain types of rock than with others. Acid igneous rocks are richer in them than basalts. Shales, in particular, which contain organic substances, are more highly radioactive than other sedimentary rocks (table IV). Potassium, thorium and radium show a tendency to concentrate in rocks with a high silicon content (table V). Tables IV, V and VI contain data on concentrations of radioactive elements in rocks.

TABLE IIIa. DATA ON PARTICLE RADIATION FROM CERTAIN NATURALLY OCCURRING RADIOACTIVE ISOTOPES

Isotope		Radiation	Number per disintegration	Energy (Mev)	Radioactive half-life	
Symbol	Name					
H^3	Tritium	β	1	0.018	12.26	years
C^{14}	Carbon-14	β	1	0.155	5,600	years
K^{40}	Potassium-40	β	0.9	1.3	1.3×10^9	years
Ra^{226}	Radium	α	1	4.78	1,600	years
Ra^{222}	Radon	α	1	5.49	3.825	days
Po^{218}	Radium A	α	1	6.00	3.05	min
Pb^{214}	Radium B	β	1	0.7	26.8	min
Bi^{214}	Radium C	β	1	3.15	19.7	min
Po^{214}	Radium C′	α	1	7.68	$1.5 \cdot 10^{-4}$	sec
Pb^{210}	Radium D	β	1	0.027	22	years
Bi^{210}	Radium E	β	1	1.17	5.0	days
Po^{210}	Polonium	α	1	5.30	138	days
Th^{232}	Thorium	α	1	3.98	$1.39 \cdot 10^{10}$	years
Ra^{228}	Mesothorium I	β	1	0.05	6.7	years
Ac^{228}	Mesothorium II	β	1	0.4–2.2	6.1	hours
Th^{228}	Radiothorium	α	1	5.4	1.9	years
Ra^{224}	Thorium X	α	1	5.6	3.64	days
Rn^{220}	Thoron	α	1	6.28	54.5	sec
Po^{216}	Thorium A	α	1	6.77	0.158	sec
Pb^{212}	Thorium B	β	0.86	0.34	10.6	hours
		β	0.14	0.58		
Bi^{212}	Thorium C	α	0.337	6.05	60.5	min
		β	0.663	2.25		
Po^{212}	Thorium C′	α	0.663	8.78	3.10^{-7}	sec
Tl^{208}	Thorium C″	β	0.337	1.79	3.1	min

TABLE IIIb. DATA ON GAMMA RADIATION FROM NATURAL RADIOISOTOPES[17]

Isotope		Energy E Mev	Number of quanta per primary disintegration n
Symbol	Name		
K^{40}	Potassium-40	1.5	0.11
Pb^{214}	Radium B	0.241	0.106
		0.294	0.240
		0.350	0.435
Bi^{214}	Radium C	0.609	0.359
		0.769	0.078
		0.934	0.038
		1.120	0.273
		1.238	0.099
		1.378	0.116
		1.509	0.039
		1.764	0.220
		1.848	0.023
		2.204	0.070
		2.432	0.025
Ac^{228}	Mesothorium II	0.336	0.0884
		0.410	0.0394
		0.458	0.0295
		0.907	0.246
		0.964	0.197
		1.587	0.118
		1.64	0.197
Pb^{212}	Thorium B	0.087	0.305
		0.238	0.330
		0.300	0.344
Bi^{212}	Thorium C	0.721	0.046
		0.81	0.104
		1.03	0.039
		1.34	0.026
		1.61	0.046
		1.81	0.046
		2.20	0.013
Tl^{208}	Thorium C′ ′	0.277	0.030
		0.510	0.073
		0.58	0.265
		0.859	0.053
		2.62	0.337

TABLE IV. RADIUM, THORIUM AND POTASSIUM CONTENTS IN VARIOUS ROCKS[16]

Type of rock	Ra^{226}, g/g x 10^{12}	Th^{232}, g/g x 10^{6}	K^{40}, g/g x 10^{2}
Igneous rocks:			
Mean value[18]	1.3	12	2.6
Granites:			3.5
North America, Greenland	1.6±0.1	8.1	
Finland	4.7±0.4	28±2.4	
Alps	4.4±0.7	33±5	
Basalts:			1.3
North America, Greenland	0.96±0.7	9.8±0.8	
Great Britain, Germany, France and Hungary	1.3 ±0.1	8.8±1.0	
Sedimentary rocks:			
Sandstone	approx. 0.3		
Limestone	up to 1.5 (1[17])	1	0.1–0.5 (0.3[17])
Alum shales in Sweden	up to 120 (60[17])	0.6–1.2 (1.5[17])	3.5[17]

TABLE V. RADIUM, THORIUM AND POTASSIUM CONTENTS IN SILICEOUS ROCKS[19]

Type of rock	Ra^{226}, g/g x 10^{12}	Th^{232}, g/g x 10^{6}	K^{40}, g/g x 10^{2}
Igneous rocks:			
Acid rocks >65% SiO_2			
Granites	3.1	20	3.4
Young granites			
(Max. level)	6.5	59	5.1
...(Granodiorite)	2.7	18	2.5
Intermediate rocks 65–55% SiO_2			
...(Diorite)	1.4	6	1.7
Basic rocks <55% SiO_2			
...(Gabbro)	0.87	5.1	0.7
Ultrabasic rocks:			
...(Peridotite)	0.52	3.3	0.8

TABLE VI. AVERAGE RADIUM, URANIUM, THORIUM AND POTASSIUM CONTENTS IN VARIOUS ROCKS[18]

Type of rock	Ra^{226}, g/g x 10^{12}	U^{238}, g/g x 10^{6}	Th^{232}, g/g x 10^{6}	K, g/g x 10^{2}
Igneous	1.3	4.0	12	2.6
Sedimentary rocks:				
Sandstones	0.71	1.2	6	1.1
Shales	1.08	1.2	10	2.7
Limestones	0.42	1.3	1.3	0.27

Radium

12. The radium concentration in rocks has been found to vary between 10^{-11} and 10^{-13} gram of radium per gram of rock.[20] The average radium content in the soil is estimated at 2 x 10^{-12} gram of radium per gram of soil;[22] the radium concentration in the soil in various parts of the United States has been found by measurement[23] to vary between 0.9 and 8.0 x 10^{-13} gram of radium per gram of soil. Tables IV to VI show radium concentrations in various minerals. The radioactivity of fresh surface water is sometimes due to radon in higher concentration than that corresponding to the radium contration, and it should be noticed that many old data on natural radioactivity of water refer to radon and not radium concentration. The natural radioactivity of drinking water is in most cases mainly due to Ra^{226}. The radium content of water sources is determined by the extent to which the water is enriched by the leaching of rocks. Water containing calcium, barium and stable strontium is particularly likely to be enriched with radium. This is one of the reasons for the wide variations in the radium content of water. The concentration varies between wide limits and characteristic values are given in table VII.

TABLE VII. CONCENTRATION OF RADIUM IN WATER

Origin	Concentration g/cm³	Ref.
Ocean	0.7–7 x 10^{-17}	23
Rivers in U.S.A.		
Average	7 x 10^{-17}	23
Mississippi	1–3 x 10^{-15}	
Public water supplies		
Sweden (tap water)	2–10 x 10^{-16}	24
U.S.A. (tap water)		
Average for 41 towns	0.42 x 10^{-16}	25
Maximum (Joliet, Ill.)	7 x 10^{-15}	23
USSR mean value (fresh water)	10 x 10^{-16}	26
Austria, Bad Gastein (tap water)	6.2 x 10^{-16}	27
Germany, Frankfurt-am-Main (tap water)	1.4–3.1 x 10^{-16}	27
Springs in special areas		
Boulder, Col., U.S.A.	3 x 10^{-10}	23
Hot Springs, Japan	7 x 10^{-10}	23
Jáchymov (Joachimstal), Czechoslovakia	5 x 10^{-10}	28
Bad Gastein, Austria	1 x 10^{-10}	29
France	0.3 x 1.4 x 10^{-13}	30

Some measurements of the Ra^{226} content in foodstuffs are given in table VIII.

TABLE VIII. Ra^{226} CONTENTS IN FOODSTUFFS[27]

Food	Ra content in g per g of food x 10^{13}
Wheat	20–26
Potatoes	67–125
Milk	0.0575/millilitre
Meat	8.0

Radon

13. Rn^{222}, an isotope of the gaseous element radon and a decay product of Ra^{226} in the uranium series, accumulates in the soil in areas where uranium-bearing minerals are present, and diffuses into the air. The average radon concentration in the soil is of the order of 10^{-13} curie/gram[31]. The rate of injection into the atmosphere is approximately 4.3×10^{-10} curies per hour per square metre of the surface (in the neighbourhood of Leningrad, USSR[26]). Seasonal changes occur in the rate of injection. The radon content of the air at ground level depends to a considerable extent on meteorological conditions. The average "equivalent" concentration of radon with its decay products in the air is approximately $1—3 \times 10^{-13}$ c/l (see table XIa). In areas with higher radioactivity (granite and other areas) the radon content may be higher than the concentrations given above by several factors of ten.

Thoron

14. Thoron (Rn^{220}) another isotope of radon is a decay product of Th^{232} and also diffuses from the ground into the air. As for radon, the concentration in air depends to a considerable extent upon meteorological conditions. The average concentration in air is approximately 0.5×10^{-13} c/l (see table XIa) but in areas with higher radioactivity it may be higher by several factors of ten.

Particle-borne radioisotopes in the atmosphere

15. In addition to radon and thoron, the atmosphere contains their solid decay products, mainly Ra B, Ra C and Th B, which attach themselves to small particles and thus constitute the natural particulate air-borne activity. The distribution of the aerosol-borne activity according to particle size is shown in table IX[17]. The particulate activity can be collected by special filters or by electrostatic precipitation. Long-lived material that remains after the decay of Th B (10.6 h half-life) constitutes only a very minor part of the total activity. Concentrations vary widely with local and meteorological factors. Extensive reference to data on radon equivalent content in both indoors and outdoors air is given by Hultqvist,[17] and a summary of some typical values has been given by Lowder and Solon[23] (see also table XIa). The particle-borne radioactivity is relevant to internal irradiation resulting from *inhalation,* since the particles, *but not the gases,* accumulate in the respiratory tract.

TABLE IX.[17] DISTRIBUTION OF RADIOACTIVITY ACCORDING TO PARTICLE DIAMETER

Diameter of particles in microns	*Radioactivity in percentage*
<0.005	5
0.005–0.015	25
0.015–0.025	50
0.025–0.035	10
>0.035	10

Potassium

16. Potassium is relatively abundant in nature. Its radioactive isotope K^{40} constitutes 0.0119 per cent of the total amount of potassium and contributes 32 β-dps per g K and 3.4γ-dps per g K. The potassium content of various rocks has been given in tables IV-VI. The potassium concentration in the soil varies between 10^{-3} and 3×10^{-2} g of potassium per g of soil. The radioactivity of ocean water is mainly due to K^{40} with a concentration of $3—5 \times 10^{-13}$ c/cm^3.

Carbon-14

17. The carbon isotope C^{14} is formed in the atmosphere as a result of nuclear reactions between cosmic rays and atmospheric nuclei. All the carbonaceous substances taking part in carbon exchange with the atmosphere have a constant equilibrium concentration of C^{14} equal to 7.21×10^{-12} c per g of carbon,[37] corresponding to a distintegration rate of 0.27 dps per g of carbon. Rocks in which such exchange cannot take place have a lower specific activity of C^{14}, depending on their geological age. Ancient carbonaceous rocks (marble and others) of geological age greater than the half-life of carbon^{14} do not as a rule contain this isotope. Observation has shown, however, that the concentration of C^{14} in nature has been increasing recently owing to contributions from a new source, namely, the explosion of nuclear weapons.[38,21]

Tritium

18. Tritium (H^3) has always been present in nature since it is formed in the atmosphere by the action of cosmic rays. The total quantity of tritium is at an equilibrium level equal to the rate of formation multiplied by the mean radioactive lifetime. The aqueous component of the cells of the human body probably has a tritium concentration equal to the one observed in foodstuffs and drinking water. The natural atomic concentration of tritium in the hydrogen of river water[39] is 5×10^{-18}. Such a tritium concentration may be calculated to result in a dose rate of 1.8×10^{-3} mrad/year to soft tissues.

IV. IRRADIATION FROM EXTERNAL SOURCES

Calculated values for gamma-ray intensities

19. The gamma radiation over rocks and soils containing known amounts of radioactive materials was first calculated by Hess.[40] Later, Hultqvist[17] calculated characteristic radiation values for minerals with the concentrations of radioactive materials given in table IV. Hultqvist developed simple numerical expressions for the gamma-ray dose, corrected for the scattered radiation. If his formulae are used to estimate the contribution to the dose rate (D, rad/year) from various concentrations of radioactive materials in the ground (s, g per g), the following expressions are obtained:

$$\left.\begin{aligned} D_{Ra} &= 18.4 \times 10^{12} \times s_{Ra} \\ D_{U} &= 6.4 \times 10^{6} \times s_{U} \\ D_{Th} &= 3.1 \times 10^{6} \times s_{Th} \\ D_{K} &= 13.3 \times 10^{2} \times s_{K} \end{aligned}\right\} \quad \ldots\ldots\ldots (1)$$

Dose rates calculated from Hultqvist's equations (1) using the data of table VI are given in table X.

TABLE X. DOSE RATES OF EXTERNAL GAMMA IRRADIATION FROM THE ELEMENTS Ra, U, Th AND K CONTAINED IN ROCKS

Type of rock	*Dose rate in mrad/year[a] from*			
	Ra^{226}	U^{238}	Th^{232}	K^{40}
Igneous rocks	24	25.8	36.8	34.6
Sedimentary rocks:				
Sandstones	13	7.7	18.4	14.6
Shales	20	7.7	30.6	36
Limestones	7.7	8.4	4	3.6

[a] Calculated from equations (1) and the data in table VI.

TABLE XI. DOSE RATES OF EXTERNAL GAMMA IRRADIATION OUT OF DOORS IN VARIOUS COUNTRIES

Country	Dose rate mrad/year	Comment	Ref.
Great Britain....	48		41
France.....	45–90		10
	180–350	Granites and shales	
United States[a]...	50–160	For 19 inhabited localities	34
Austria.....	58		35
Sweden[a].....	85	Stockholm street	36
	60–120	Igneous rocks	
	50	Clay	

[a] Values obtained by subtraction of 28 mrad/year for cosmic rays.

TABLE XIa. CONCENTRATIONS OF RADON AND THORON IN EQUILIBRIUM WITH THEIR DECAY PRODUCTS PRESENT IN THE AIR IN VARIOUS REGIONS AND CORRESPONDING CALCULATED DOSES

	Average concentration in c/l x 10^{13}		Dose in mrad/year		
Place of observation	Rn	Tn	Rn	Tn	Ref.
Czechoslovakia....	8.0		11		28
Great Britain.....	3.0		4.3		32
Japan.....	1–2.5		1.4–3.5		11
France.....	2.0	0.6	2.8	0.8	34
Austria.....	1–3		1.4–4.3		35
Sweden.....	1.0		1.4		36
USSR.....	1.0	0.5	1.4	0.7	26

Measured total outdoor radiation

20. Total gamma ray and cosmic ray intensities have been measured by various authors using ionization chambers. The experimental dose rates are given in table XI and may be compared with calculated values. Where necessary, gamma ray figures in table XI have been obtained by subtracting an average value of 28 mrad/year for cosmic rays.

TABLE XII. DOSE RATES OF EXTERNAL GAMMA IRRADIATION IN SWEDISH BUILDINGS[17, 14]

Building material (Outer walls)	Mean dose rate, in mrad/year[a]		
	Centre of room	Highest reading	Lowest reading
Wood.....	49	57	48
Brick.....	104	112	99
Light-weight concrete..... (containing alum shale)	172	202	158

[a] Using table VI of ref. 17 and excluding cosmic rays (1.9 ion-pairs/cm^3·sec).

TABLE XIII. DOSE RATES OF EXTERNAL GAMMA IRRADIATION INSIDE BUILDINGS IN GREAT BRITAIN[41]

Type of Building	Sites measured	Dose rate, mrad/year: Local gamma rays	Mean
1. All granite	(a) Aberdeen, Laboratory.....	107	
	(b) Aberdeen, bell tower.....	99	102
	(c) Aberdeen, entrance hall....	101	
2. Concrete or brick	(a) Aberdeen, rooms on various floors.....	73	
	(b) Leeds, rooms in hospital building.....	81	78
	(c) Leeds, single storey laboratory.....	80	
	(d) Leeds, various rooms in house	77	

TABLE XIV. DOSE RATE OF EXTERNAL GAMMA IRRADIATION INSIDE BUILDINGS IN AUSTRIA[35]

Type of building	Dose rate, mrad/year
Wooden house.....	54–64
All granite.....	85–128
Brick (brick or concrete).....	75–86

External irradiation in buildings

21. External irradiation by gamma rays is greater inside buildings of brick, concrete, shales and other materials than out of doors because of the radioactive elements contained in these materials. Some increase in the dose may be produced by the accumulation of radon or thoron as a result of poor ventilation in the buildings. On the other hand, the buildings reduce the dose of external irradiation by absorbing the radiation from sources outside the buildings. Tables XII, XIII and XIV indicate the dose rates of external gamma irradiation inside buildings, table XV the dose rate from radon and thoron present in the air in buildings (*without ventilation*).

TABLE XV. DOSE RATE OF EXTERNAL GAMMA IRRADIATION FROM Rn AND Tn PRESENT IN THE AIR IN SWEDISH BUILDINGS

Material (outer walls)	Average concentration in c/l x 10^{13}		Dose rate, mrad/year[a]	
	Rn	Tn	Rn	Tn
Wood.....	0.527	0.0276	7.5	0.4
Brick.....	0.909	0.091	13	1.3
Light-weight concrete (containing alum shale)	1.86	0.0959	26.4	1.35

[a] Table XV of ref. 17 was used, the calculation being made according to equation (2).

22. The gamma radiation from radioactive material in the air can be calculated by Hultqvist's relations[17]

$$\left.\begin{aligned} D_{Rn} &= 14.2\times10^{12}\times C_{Rn}\ \text{mrad/year} \\ D_{Tn} &= 14.0\times10^{12}\times C_{Tn}\ \text{mrad/year} \end{aligned}\right\} \quad \ldots\ldots (2)$$

where C is the concentration of radon and thoron in curies per litre of air. Values corresponding to the concentrations of columns 2 and 3 of table XIa are given in columns 4 and 5.

Special areas

23. Much higher values of the external radiation have been found in some areas where the thorium content in the soil is particularly high.

24. The region of Kerala (India), which is approximately 100 km^2 in area (about 200 km long and several hundred metres wide) has a population of about 100,000. The available measurements[43] have been made in ten villages of the intensity of the radiation *inside buildings* of three types constructed of various materials typical of the region. The basic materials are brick and cement (A), clay (B) and wood (C). The results of the measurements and corresponding calculated doses are given in tables XVII and XVIIa. The mean value of the individual dose is 1,300 mrad/year, calculated from the equation

$$\bar{D} = \frac{\sum_r P_r X_r}{\sum_r P_r}$$

where P_r is the population in village r and X_r is the mean value of the dose in village r.

TABLE XVI. EXTERNAL IRRADIATION IN SPECIAL AREAS

Geology	*Location*	*Area*	*Population*	*External irradiation mrad/year*	*Ref.*
Monazite sand alluvial deposits	Brazil States of Rio de Janeiro and Espirito Santo (Outdoor)	Sequence of intermittent coastal strips each several km long and several hundred metres wide	50,000	Average 500 peak values 1,000	42
Mineralized volcanic intrusives	Brazil States of Minas Gerais and Goias (Outdoor)	Approximately 6 km² in a dozen scattered places	Pasture land, scattered farms, 1 village with 350 inhabitants	Average 1,600 peak values 12,000	42

TABLE XVII. DOSES OF EXTERNAL GAMMA IRRADIATION INSIDE BUILDINGS AT TEN INHABITED LOCALITIES IN THE KERALA REGION (INDIA)[43]

Name of village	*Area of village in 1,000 sq. metres*	*No. of population (in thousands)*	*Type of house*	*No. of houses*	*Mean dose rate mrad/year*
1. Kadiapattam.....	83	6	B, C	17	2,814
2. Manavalakuruchi..	660	11	A, B, C	36	2,164
3. Muttam.....	208	6	A, B, C	21	736
4. Midalam.....	370	10	A, C	40	1,573
5. Vilingem.....	540	10	A, B, C	22	131
6. Karamanal.....	41.5	2	A, B, C	19	1,283
7. Kavalem.....	8.3	1	C	1	814
8. Kullatoor.....	54	2	A, B	10	370
9. Vettoor.....	29	3	B	10	527
10. Varkala.....	41.5	1	A	12	1,376
		52		193	

TABLE XVIIa. DOSES OF EXTERNAL GAMMA-IRRADIATION INSIDE BUILDINGS OF VARIOUS TYPES IN THE KERALA REGION (INDIA)[43]

	Type of house and building material	*No. of houses*	*Percentage of total number of houses in the region*	*Dose, mrad/year*	
				Maximum value	*Minimum value*
Type A.	Brick..... Cement.....	73	15	2,890	66
Type B.	Clay.....	62	60	3,150	105
Type C.	Wood..... Bamboo..... Palm.....	52	25	3,950	145

TABLE XVIII. MEAN VALUES OF DOSES OF EXTERNAL IRRADIATION FROM VARIOUS SOURCES OF RADIATION

Source of radiation	*Dose rate, mrad/year*		
	Mean value	*Extreme values*	
1. Cosmic rays.....	28	20–34	Table I
Ordinary regions:			
2. Gamma rays over rocks.....	73	25–120	Table X
3. Gamma rays out of doors.....	70	48–160	Table XI
4. Gamma rays from aerial sources...	3	1.4–11	Table XIa
Active regions:			
5. Gamma rays, granitic regions in France.....	265	180–350	Table XI
6. Gamma rays, monazite region, Kerala in India.....	1,270[a]	131–2,814	Table XVII

[a] By subtraction of cosmic ray dose of 28 mrad/year from total.

Summary of irradiation by external sources

25. An approximate estimate of the level of external irradiation from natural sources can be made from the above material. The measured doses out-of-doors in various regions give a mean dose equal to 70 mrad/year (excluding highly radioactive regions). On the other hand, a value for the mean dose over rocks of 73 mrad/year may be derived by calculation from the mean concentrations of radioactive elements in the most widely distributed rocks (Table X). Thus in normal regions the mean dose can be estimated at approximately 70 mrad/year. Summary data on external irradiation are given in Table XVIII, column 3 of which indicates mean doses, column 4 the spread of typical values, and column 5 of the reference to the data used in estimating the mean level of irradiation.

Gonad and bone doses

26. In calculating the doses to the gonads and bones from external gamma irradiation, a coefficient (shielding factor) must be introduced to allow for the partial absorption of gamma radiation by outer tissues. Spiers[32] gives the following estimates for the gonads:

TABLE XIX. GONADAL SHIELDING FACTOR FOR GAMMA RAYS IN THREE POSITIONS: HORIZONTAL, SITTING AND STANDING

Position	Shielding factor			
	Female	Average	Male	Average
Horizontal	0.52		0.67	
Sitting	0.58	0.56	0.70	0.70
Standing	0.59		0.72	

Mean factor for both sexes: 0.63

The mean shielding factor in the case of bones will also be taken here to be 0.63

27. Estimated aggregate values can now be given for the gonad and bone doses from natural sources of radiation—cosmic rays and radioactive elements. The populations are subdivided into three groups according to level of irradiation: people living in normal regions—*i.e.* regions where the level of irradiation is not more than 100 mrad/year; population groups living in active regions with a higher level of irradiation, up to 500 mrad/year; and lastly, persons living in regions with a high level of irradiation—over 500 mrad/year. Such a division is artificial, but is useful in considering the biological effects of irradiation.

TABLE XX. MEAN DOSE TO GONADS AND BONES FROM NATURAL EXTERNAL SOURCES IN NORMAL REGIONS AND MORE ACTIVE REGIONS

Region	Population in millions	Aggregate mean dose mrem/year*
1. Normal regions	2,500	75
2. Granitic regions in France	7	190
3. Monazite region, Kerala in India	0.1	830
4. Monazite region Brazil	0.05	315

* Using a shielding factor of 0.63 for γ-rays and a dose rate of 28 mrem/year due to cosmic rays.

V. INTERNAL RADIOACTIVE SOURCES

Radioactive substances in the body

28. The radioactive isotopes C^{14} and K^{40} are normal constituents of the human body. Ra^{226} is taken up from food and water and is present with its decay products in the body. Radioactive material from the atmosphere enters the respiratory tract by inhalation and some airborne particulate material is retained.

Carbon-14

29. The total carbon content of the body is approximately 18 per cent or 12.6 kg for a total body weight of 70 kg. Therefore, the amount of C^{14} for a total body weight of 70 kg is of the order of 0.1 mc.

Potassium-40

30. The total potassium content of the body has been given as 0.185 per cent or 130 g by Sievert,[44] as the average value of a series of observations by several authors. While individual values range between 0.12 and 0.35 per cent, the majority of results group together rather closely around the average value given above.

31. The concentration of radioactive potassium in various organs, according to Forbes and Lewis,[45] is given in table XXI.

TABLE XXI. POTASSIUM CONTENT OF VARIOUS ORGANS OF MAN[45]

Organ	Percentage of total body weight	Concentration in percent
Skin	6.5	0.16
Skeleton	13.4	0.11
Tibia	1.4	0.05
Muscles	39.6	0.31
Nervous system	2.1	0.30
Liver	2.3	0.23
Heart	0.6	0.19
Lungs	2.2	0.27
Kidneys	0.4	0.23
G.I. tract	1.5	0.14
Adipose tissue	21.4	0.06
Remainder	6.4	0.18
Total body weight: 73 kg		0.2

Radium

32. Radium, like calcium, is selectively incorporated in bone. As the amount of radium daily ingested in food has been estimated[46] to be around 1.6×10^{-12} g, the uptake through drinking water is significant only if the radium concentration in the water is at least 10^{-15} g Ra^{226}/cm^3. Consumption of such water may result in an increased body burden of radium, but, as the concentration is normally lower, the body content of radium is believed to depend in most cases on the radium content of the food. The following figures have been reported for the total radium content in the human body: 1.6×10^{-10} g[47], 3.3×10^{-10} g[27], and $0.4—3.7 \times 10^{-10}$ g[48]. Muth[27] (table XXII) has recently published values of radium concentrations in different tissues which seem to indicate that a substantial proportion of the radium burden is located in soft tissues. These values have not yet been confirmed in other laboratories.

TABLE XXII. RADIUM CONTENT IN VARIOUS TISSUES[27]

Tissue	Number of samples	Ra content per g of untreated tissue		
		Minimum value	Mean value	Maximum value
Bones	6	4.9	9.7	16
Lungs	4	1.6	2.3	3.5
Liver	4	0.4	3.4	11
Spleen	3	1.8	4.6	7.4
Muscles	2		1.4	
Testicles	28		0.6	

Particulate air-borne activity

33. Because the disintegration products of radon and thoron are present in the air attached to the particles of aerosols, the amount of radioactive air-borne material retained in the respiratory tract depends upon the filtering properties of this tract for particles of different sizes. Figure 1 shows some characteristic average retention values for particles of different sizes taken from a graph given by Hultqvist (ref. 17, p. 46). Virtually all the activity is concentrated in particles of no more than 0.04 microns in diameter and up to about 70 per cent of such particles will be retained in the lungs according to the graph.

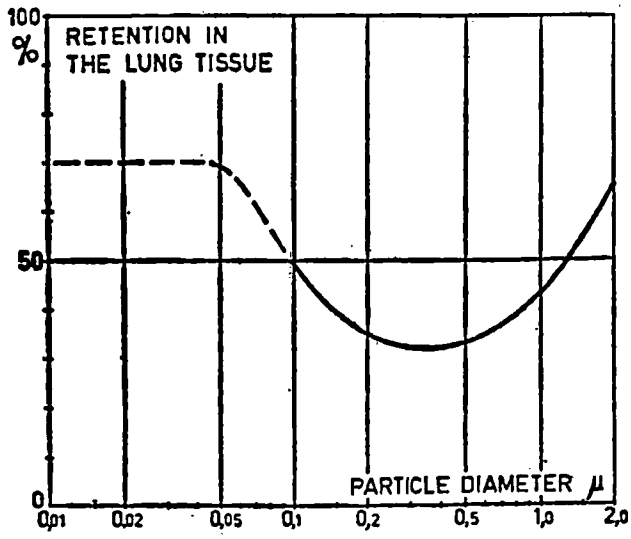

Figure 1 Approximate "median curve" for the alveolar retention. The broken line refers to that magnitude range for which no experimental investigations are available. (Reproduced from Hultqvist, ref. 17, page 46.)

VI. Irradiation from internal sources

34. The dose rates from potassium and carbon are approximately uniform over the body and are calculated from the known concentration of these elements and the specific energies of their radiations. Calculated dose rates are given in table XXIII, using the following parameters:

K^{40}: energy of quanta E γ = 1.5 Mev, 0.1 quantum per disintegration, average energy of β particles $\bar{E}\beta$ = 0.6 Mev, 50 per cent of the energy of the gamma quanta is absorbed by the tissues;

C^{14}: average energy of β particles $\bar{E}\beta$ = 0.067 Mev.

35. In calculating the doses of irradiation from radium taken up into the organism, only the alpha-particle energy is taken into account as a rule, and all the radium is assumed to be in the bones. Figures published recently[27] (table XXII) present a rather different picture of the distribution of radium in the organism, but this has not yet been confirmed by other researchers. The local distribution of radium in bone tissue is of considerable importance in estimating osteocyte doses[49,50] and it is generally studied by radioautography but at the level of the natural concentration of radium in the bones, this method does not yield reliable results: the data published on radium distribution have been obtained with relatively large concentrations of radium. The question therefore arises whether a similar picture of radium distribution in bone tissue would be obtained with small concentrations. There is as yet no satisfactory answer to this question and it is accordingly assumed here that when radium is present in natural concentrations in non-active regions, its distribution in bone tissue is uniform.

36. As the range of alpha-particles in the tissues is approximately of the same order as the diameter of the cavities in bone tissue, the relationship between alpha-particle range and cavity size must be taken into account in calculating the dose. According to Spiers[49] this may be reduced to introducing into the equation for calculating the dose a geometric factor having different values for bones of differing structure. Spiers (*op. cit*) expresses the equation for calculating the bone dose in the case of alpha particles from radium in the bones in the following form (in which 50 per cent of the energy is assumed to come from disintegration products):

$$D = 1.78 \times 10^{11} \bar{F} m \text{ mrad/year}$$

where $\bar{F}$ is the mean geometric factor, m the radium content in the bones in grams of radium per gram of bone.

37. For a body burden of 10^{-10} g Ra^{226}, which is average for normal (non-active) regions, the numerical value of the osteocyte dose is then

$$D = 38 \text{ mrem/year}$$

where $\bar{F}$ = 1.48, using an RBE = 10. The mean dose to the bone marrow is largely due to the β activity of the radium decay products, and may be estimated to be approximately 0.5 mrem/year

$$D\beta = 0.5 \text{ mrem/year}$$

38. The dose of irradiation by radon and thoron and their distintegration products is considerably greater (as compared with external irradiation) if these substances are taken up into the organism with inhaled air. In this case the lungs are the critical organ. Assuming, in accordance with the data given above, that 60 per cent of the aerosol particles carrying the radioactivity of the disintegration products of Rn and Tn are retained in the tissues and that the volume of the lungs is 3,000 cm^3 and their weight 800 g, the numerical value of the lung dose can be calculated, according to Hultqvist,[14,17] from the following equations:

$$\left.\begin{aligned} D_{Rn} &= 5.0 \times 10^{14} C_{Rn} \text{ mrem/year} \\ D_{Tn} &= 66.5 \times 10^{14} C_{Tn} \text{ mrem/year} \end{aligned}\right\} \quad \ldots\ldots (3)$$

Table XXIII. Radioactivity of the body and tissue doses from K_{40} and C^{14} (*standard man, 70 kg*)

Element	*Weight in percentage*	*Weight in g*	*Radiation*	*Activity in curies x 10^8*	*Gonad dose, mrad/year*	*Osteocyte dose mrad/year*
K.....	0.20	140				
K^{40}.....	$2.38 \cdot 10^{-5}$	$1.66 \cdot 10^{-2}$	β	10.4	16.5	9.0[a]
			γ	1.15	2.3	2.3
C.....	18.0	12,600				
C^{14}.....	$2.8 \cdot 10^{-11}$	$1.96 \cdot 10^{-8}$	β	9.0	1.6	1.6

[a] Using the potassium content in the bones according to Table XXI.

TABLE XXIV. DOSES TO LUNGS FROM RADON AND THORON IN THE AIR
(based on measurements carried out in Sweden)

Outer wall	Concentration of Rn in c/l x 10^{12}		Concentration of Tn in c/l x 10^{12}		Dose in mrem/year: Rn		Tn	
	Assuming equilibrium	With ventilation 10^{-3} sec	Assuming equilibrium	With ventilation 10^{-3} sec	In equilibrium	With ventilation	In equilibrium	With ventilation
Wood	0.527	0.537	0.0278	0.136	263	73	185	52
Brick	0.909	0.913	0.0910	0.450	453	128	605	173
Light weight concrete (contain. alum shale)	1.86	1.86	0.0959	0.461	930	262	640	178

where C is the radon or thoron concentration in curies/litre, and radioactive equilibrium is assumed. In another case—that of ventilated buildings, where the air in the building is renewed every seventeen minutes, i.e. 10^{-3} of the air is renewed per second—Hultqvist obtained the following equations:

$$\left.\begin{aligned} D_{Rn} &= 1.4\times10^{14}\ C_{Rn}\ \text{mrem/year} \\ D_{Tn} &= 3.85\times10^{14}\ C_{Tn}\ \text{mrem/year} \end{aligned}\right\} \quad \ldots\ldots(4)$$

where C is the radon or thoron concentration in curies/litre. The results of measurements carried out in three types of buildings in Sweden are given in table XXIV; the doses were calculated from equations (3) and (4).

39. Aggregate figures for internal irradiation give the following dose rates: gonads 20 mrem/year and osteocytes 50 mrem/year.

CONCLUSION

40. Since the data given in the text relate to individual inhabited regions and are naturally far from complete, it may be asked whether they can be considered representative for the whole population of the world. As far as the level of irradiation from sources such as cosmic rays and radioactive elements that are constituents of the body (potassium and carbon) is concerned, the answer is in the affirmative. In the case of other sources of external and internal irradiation present in the soil, water and air are capable of being taken up into the organism, the level of irradiation depends on the geological features of the region concerned and therefore varies considerably from one place to another. In this case, only a very approximate estimate of the mean level of irradiation is possible. The results of such an approximation are given in table XXV.

TABLE XXV. DOSES OF EXTERNAL AND INTERNAL IRRADIATION FROM NATURAL SOURCES OF RADIATION

Irradiation	Dose mrem/year: To gonads and other soft tissues[a]	To bones	Comment
External irradiation:			
Cosmic rays	28	28	At sea level
Gamma rays out-of-doors	47	47	
Internal irradiation:			
K^{40}	19	11	
C^{14}	1.6	1.6	
Ra^{226}	?	38	
Total irradiation from all sources	95	125	At sea level

[a] Including bone marrow since the contribution from Ra in bone does not exceed about 0.5 mrem per year.

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Appendix

LIST OF SCIENTIFIC EXPERTS

The scientific experts who have taken part in the preparation of the report while attending Committee sessions as members of national delegations are listed below. The Committee must also express its appreciation to the many individual scientists not directly connected with national delegations whose voluntary co-operation and good will contributed in no small measure to the preparation of the report.

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back to first page