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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 A

DEFINITIONS OF QUANTITIES, UNITS AND SYMBOLS

1. The 1956 report of the International Commission on Radiological Units and Measurements[1] gives the following definitions of quantities and units used in radiological physics.*

"1.1 *Absorbed dose* of any ionizing radiation is the energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest.

"1.2 The unit of absorbed dose is the *rad*. One rad is 100 ergs/g.

"1.3 *Integral absorbed dose* in a certain region is the energy imparted to matter by ionizing particles in that region.

"1.4 The unit of integral absorbed dose is the *gram rad*. One gram rad is 100 ergs.

"1.5 *Absorbed dose rate* is the absorbed dose per unit time.

"1.6 The unit of absorbed dose rate is the *rad per unit time*.

"1.7 *Exposure dose of X- or gamma radiation* at a certain place is a measure of the radiation that is based upon its ability to produce ionization.

"1.8 The unit of exposure dose of X- or gamma radiation is the *roentgen* (r). One roentgen is an exposure dose of X- or gamma radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign.

"1.9 *Exposure dose rate* is the exposure dose per unit time.

"1.10 The unit of exposure dose rate is the *roentgen per unit time*.

"1.11 *Intensity of radiation* (radiant energy flux density) at a given place is the energy per unit time entering a small sphere of unit cross-sectional area centred at that place.

"1.12 The unit of intensity of radiation may be *erg per square centimeter second*, or *watt per square centimeter*.

"1.13 The unit of quantity of radioactive material, evaluated according to its radioactivity, is the *curie* (c). One curie is a quantity of a radioactive nuclide in which the number of disintegrations per second is 3.700×10^{10}.

"1.14 *Specific gamma-ray emission* (specific gamma-ray output) of a radioactive nuclide is the exposure dose rate produced by the unfiltered gamma rays from a point source of a defined quantity of that nuclide at a defined distance.

"1.15 The unit of specific gamma-ray emission is the *roentgen per millicurie hour* (r/mch) *at 1 cm*.

"1.16 *Linear energy transfer* (LET) is the linear rate of loss of energy (locally absorbed) by an ionizing particle traversing a material medium.

"1.17 Linear energy transfer may be conveniently expressed in *kilo electron volts per micron* (kev/μ).

"1.18 *Mass stopping power* is the loss of energy per unit mass per unit area by an ionizing particle traversing a material medium.

"1.19 Mass stopping power may be conveniently expressed in *kilo electron volts per milligram per square centimeter* (kev cm^2/mg)."

2. The RBE symbol is described in the I.C.R.U. report, in the following way:

"2.1 *RBE* (relative biological effectiveness) is used to compare the effectiveness of absorbed dose of radiation delivered in different ways. It has been commonly represented by the symbol η. It signifies that m rads delivered by a particular irradiation procedure produces a biological response identical with that produced by mη rads delivered by a different procedure.

The statement that 'the RBE of α radiation relative to γ radiation is 10' signifies that m rads of α radiation produces a particular biological response in the same degree as 10m rads of γ radiation. This statement may be further summarized as $\eta \frac{\alpha}{\gamma} = 10$.

The concept of RBE has a limited usefulness because the biological effectiveness of any radiation depends on many factors. Thus the RBE of two radiations cannot in general be expressed by a single factor but varies with many subsidiary factors, such as the type and degree of biological damage (and hence with the absorbed dose), the absorbed dose rate, the fractionation, the oxygen tension, the pH, and the temperature.

"2.2 *RBE dose* is equal numerically to the product of the dose in rads and an agreed conventional value of the RBE with respect to a particular form of radiation effect. The standard of comparison is X- or gamma radiation having a LET in water of 3 kev/μ delivered at a rate of about 10 rad/min.

"2.3 The unit of RBE is the *rem*. It has the same inherent looseness as the RBE and in addition assumes conventional and not necessarily measured

* Symbols and nomenclature. There are numerous national and international bodies that have reached varying degrees of acceptance of the use of symbols and units for physical quantities. However, there is no universal acceptance of any one set of recommendations. It is suggested that each country modify the symbols used herein, in accordance with its own practices. Thus one may write: kev, keV, or Kev; ^{14}C or C^{14}; rad per unit time, rad per time, or rad divided by time; rad/sec, rad/s, or rad·s^{-1}; etc. The most generally accepted system of symbols and units may be that contained in document UIP 6 (1955) prepared by the International Union of Pure and Applied Physics. These are in fairly close agreement with the recommendations of the International Standardization Organization project ISO/TC 12, the Conférence Générale de Poids et Mesures, Union Internationale de Chimie Pure et Appliquée, and the International Electrotechnical Committee.

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values of RBE. It is therefore recommended that its use be restricted to statements relating to radiation protection. For example the statement might be made:

The permissible weekly whole body RBE dose is 0.3 rem regardless of the type of radiation to which a person is exposed.

Should occasion arise when results have been evaluated with other than agreed conventional values of RBE, the values used should be clearly stated.

In the case of mixed radiations the RBE dose is assumed to be equal to the sum of the products of the absorbed dose of each radiation and its RBE:

RBE dose in rems = Σ [(absorbed dose in rads) x RBE]."

Reference

1. International Commission on Radiological Units and Measurements (ICRU): Report of the ICRU, 1956. U.S. National Bureau of Standards, Handbook 62, Washington 1957.

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.

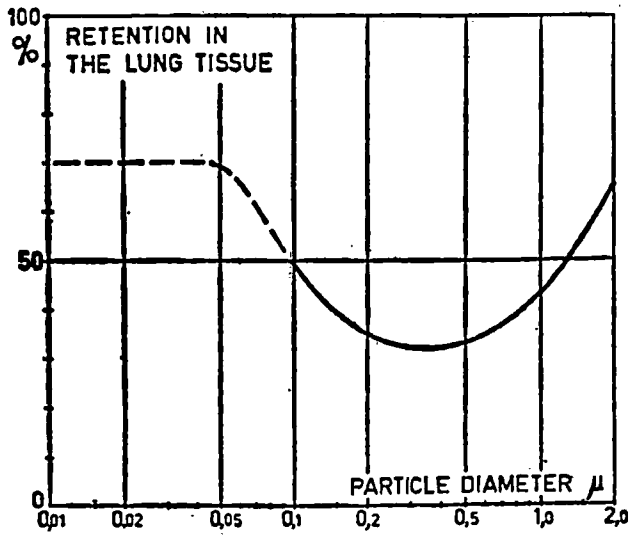

Figure 1 Approximate "median curve" for the alveolar retention. The broken line refers to that magnitude range for which no experimental investigations are available. (Reproduced from Hultqvist, ref. 17, page 46.)

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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Annex C

MAN-MADE SOURCES

(Other than environmental contamination)

TABLE OF CONTENTS

I. Introduction

1. The various estimates of genetically significant dose which have been available to the Committee are discussed in this annex, and some preliminary estimates of mean marrow doses are also given. The presentation follows, as far as possible, the scheme given in chapter III.

II. Medical uses of X-rays and radioactive materials

2. Medical uses of X-rays and radioactive materials are responsible for the largest man-made exposures of many populations at the present time, the doses possibly ranging up to more than 100 per cent of the dose due to natural sources in some of the countries for which estimates have been made.

3. The medical exposure is mainly an exposure of patients undergoing diagnostic examinations or radiation therapy. It is also an occupational exposure, from which, however, the dose to the population as a whole is comparatively very small. This occupational exposure is treated separately in paragraphs 72-83.

4. In view of the importance of the medical exposure, the Committee invited the International Commission on Radiological Protection (ICRP) and the International Commission on Radiological Units and Measurements (ICRU)

"(*a*) To consider and discuss the question of how to arrive at reliable data indicating the doses to different parts of the body (particularly the gonads) received by individuals and, in the aggregate, by large population groups due to medical uses of ionizing radiations and

"(*b*) To examine what recording system, if any, is at present feasible for the determination of the relevant dose values."

The two Commissions formed a joint study group to consider and prepare a report[1] for the Committee on these problems.* The following is the summary of their report.**

"*1. Preliminary considerations*

"(*a*) The principal objective has been to recommend methods for the evaluation of the genetically significant annual gonad dose, G_m, which arises from medical uses of ionizing radiation.

"(*b*) It is assumed that the magnitude of the significant gonad dose due to natural background may be taken as a standard of reference and that 25 per cent of this dose is the greatest absolute accuracy which need be aimed at for an initial determination.

"(*c*) While not always yielding values strictly in terms of G_m as defined in paragraph 4 (of the ICRP/U Study Group report), the preliminary surveys which have already been conducted have yielded values of G_m of the order of 100 mrad (probable value) and 50 mrad (minimum value) for the U.S.A. and of the order of 20-40 mrad (minimum values) for Denmark, Sweden and the United Kingdom (England and Wales).

"(*d*) These surveys show at present that diagnosis makes a much larger contribution than therapy, and that some 85 per cent of the diagnostic dose arises from 6 or 7 types of examination, constituting only about 10 per cent of all examinations of the types listed.†

"(*e*) It follows that, as regards dosimetry, those 6 or 7 types call for special consideration in future surveys.

"*2. Recommendations*

"(*a*) It is recommended that the basic studies be continued and extended, making use of suitable ionization dosemeters in order to obtain data that may be used in the preparation of standard tables which give the average gonad dose in mrad corresponding to each type of diagnostic and therapeutic use of ionizing radiation. Special attention should be paid to the six or seven types of diagnostic examinations which account for 85 per cent of the gonad dose.

"(*b*) It is recommended that in all countries the analysis of film records, together with the results of 2 (a) above, be used as a first approximation to G_m. If the dose so calculated exceeds a few per cent of natural background, a detailed analysis is recommended.

"(*c*) It is recommended that where required, the more detailed analysis should be obtained by means of a sampling programme, operated through personal contact between trained surveyors and both medical institutions and radiation practitioners, and that data obtained from this sampling programme should be used for the determination of G_m.

"(*d*) It is recommended that prior to initiating the main sampling programme (referred to in 2 (c) above), a number of presurveys should be conducted in order to obtain information useful in planning and conducting the programme.

"(*e*) It is recommended that in preparation for the main sampling programme, careful planning and instructional programmes should be initiated by a properly selected group of medical physicists, health physicists, radiologists, statisticians, biometricians, and surveyors. Appropriate dosemeters should be made available to the surveyors who should be instructed in their use.

"(*f*) It is suggested that surveys will result in improved practices with a consequent reduction in exposure. This is likely to be a most important consequence of all surveys, and specific suggestions are made for the reduction of gonad dose due to diagnostic procedures.

* 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.

** The references to pages in the Joint Study Group report have been omitted here.

† The list referred to here excludes dental examinations and mass miniature radiography.

"3. Not recommended

"The systematic recording and registration of the radiation received by every member of the population is not recommended."

5. The ICRP/ICRU Joint Study Group was mainly concerned with how the genetically significant dose should be assessed. This problem is discussed in further detail in this report. As the scheme of computation is common for all types of exposure, it is presented separately, before the various classes of exposure are discussed.

The genetically significant dose

Calculations

6. A general definition of genetically significant dose has been given in chapter II. Approximations must be made to calculate this dose, the most obvious being consideration of groups rather than individuals. It is convenient to start with the approximate definition*

$$D = \frac{\sum_j \sum_k (N_{jk}^{(F)}\, w_{jk}^{(F)}\, d_{jk}^{(F)} + N_{jk}^{(M)}\, w_{jk}^{(M)}\, d_{jk}^{(M)})}{\sum_k (N_k^{(F)}\, w_k^{(F)} + N_k^{(M)}\, w_k^{(M)})} \qquad (1)$$

where D = (annual) genetically significant dose,

N_{jk} = (annual) number of individuals of age class k, subjected to class j exposure,

N_k = total number of individuals of age-class k

w_{jk} = future number of children expected by an exposed individual of age-class k subsequent to a class j exposure,

w_k = future number of children expected by an average individual of age-class k,

d_{jk} = gonad dose per class j exposure of an individual of age-class k,

(F) and (M) denote "female" and "male" respectively.

7. For the practical work, Equation (1) can be simplified considerably, the first step being to replace the denominator by $w \cdot N$, where

$$w = \frac{N^{(F)}}{N} \cdot w^{(F)} + \frac{N^{(M)}}{N} \cdot w^{(M)} \qquad (2)$$

and

$$w^* = \frac{1}{N^*} \sum_k w_k^* N_k^* \qquad (3)$$

In the last expression, * denotes the sex. N is the tota number of individuals of the population. It should be noticed that $w \cdot N$ is about twice the future number of children expected by the present population even though the value of w may be as low as 0.8.

8. As equation (1) has w^* in both the numerator and denominator, the numerical value of w has no direct relevance, and all terms can be expressed by help of the ratio w_{jk}/w. For understanding of the demographic background, however, it is valuable to realize that w must be calculated from the sum of the age-group products $w_k^* \cdot N_k^*$ for a population, which means that an assumption has to be made regarding the expected *future* number of children (w_k^*) of an individual in any specified age-group.

9. The assumption could be that the average individual will have a future annual child-expectancy expressed by the present specific annual birth rate. This makes it possible to calculate, by summation, the total future expected number of children of an individual of any age, and hence also the mean for any age-group. If significantly less than unity, the probability of an individual of age a to reach age t should also be considered. This gives

$$w_a^* = \sum_{t=a}^{\infty} c_t^* \cdot \Delta t \cdot P_a^*(t) \qquad (4)$$

where

w_a^* = expected future number of children of an individual of age a. With knowledge of the function w_a^* of age, the average w_k^* for any age-group k can be calculated,

c_t^* = age-specific annual birth rate, i.e., annual expected number of children of an individual of age-group t,

Δt = number of years included in age-group t,

$P_a^*(t)$ = probability of an individual of age a to reach age (group) t.

10. It must be noted that c_t^* may have a tendency to change considerably before an average individual of a specified age has reached the age-group in question. As it is, however, difficult to predict the values for the future, c_t^* has been assumed not to vary with time.

11. $W^* = w_{a \to 0}^*$ is the number of children expected by the average individual during his whole life. The range of w^* is normally 0.8–2, and the range of W^* is 2–4 for most developed countries. The ratio W/w ranges from 1.5 to 3.

12. The female and the male contribution to the genetically significant dose can both be written

$$D^* = \frac{1}{wN} \sum_j \sum_k N_{jk}^* w_{jk}^* d_{jk}^* \qquad (5)$$

13. If the gonad dose due to an examination of type j is nearly uniform for all age-classes k, then

$$d_{jk}^* = d_j^* \qquad (6)$$

approximately for all k, and Equation (5) reduces to

$$D^* = \frac{1}{wN} \sum_j d_j^* \sum_k N_{jk}^* w_{jk}^* \qquad (7)$$

or

$$D_j^* = d_j^* \cdot \frac{1}{wN} \sum_k N_{jk}^* w_{jk}^*$$

where D_j^* is the contribution from type j examination of the specified sex to the genetically significant dose. This again can be written as

$$\boxed{D_j^* = d_j^* \cdot \frac{N_j^*}{N} \cdot \frac{w_j^*}{w}} \qquad (8)$$

which is the expression that has been used for presentation of the data in most of appendices I–X.

14. The necessary information to make it possible to calculate D_j^* by help of Equation (8) is:

(*a*) d_j^* = the mean gonad dose per individual undergoing class j examination,

(*b*) N_j^*/N = the relative frequency of class j examination, i.e., the number of examinations *per capita*, per year,

* The degree of approximation involved in the use of equation (1) depends on the definition of classes j. In theory, there need be no approximation since the classes may be made so restrictive as to include only one individual per class.

(*c*) w_j^*/w = the relative child-expectancy of the average individual undergoing class j examination.

The formula is applicable also to foetal exposure ($w_j = W$) which must not be overlooked.

15. Often d_j varies considerably from hospital to hospital. Most of the uncertainty in estimates of D_j is probably due to the difficulty of estimating a reliable average of d_j for a population.

16. If there are no data on the child-expectancy of the patients, an approximate estimate of D_j^* may be made, under the assumption that the child-expectancy is not influenced by the nature of the condition for which the patient is examined. w_j^* can then be calculated from the age-distribution of the patients and the normal child-expectancy for each age-group,

$$w_j^* = \frac{\sum_k w_{jk}^* N_{jk}^*}{N_j^*} \approx \frac{\sum_k w_k^* N_{jk}^*}{N_j^*} \qquad (9)$$

where w^* can be taken from Equation (4). If w_j^*/w is not given in the primary material, it may be recalculated from N_j^*/N, d^* and this approximation of D_j^*, but will in that case reflect only variations in the age-distribution of the patients examined and not indicate any dependence of child expectation on type of examination.

17. In the case where the age-distribution in an examination class is not known, a yet more simplified assumption must be used, namely

$w_k^* = W^*$ for all persons below mean age of child-bearing

$w_k^* = 0$ for all persons above mean age of child-bearing

If n is the total number in the population below the mean age of child-bearing, it follows from Equation (3) that

$$w^* = \frac{n^*}{N^*} \cdot W^* \qquad (10)$$

which is also, indirectly, a definition of the "mean age of child-bearing". Equation (8) reduces approximately to

$$D_j^* = \frac{n_j^*}{n} \cdot d_j = \frac{N}{n} \cdot \frac{n_j^*}{N} \cdot d_j \qquad (11)$$

Statistical data

18. The scheme of calculation presented in paragraphs 6-17 is the one that has been followed by the Committee in evaluating reported data on gonad exposure. The difficulty of applying any standardized method of calculation to a large amount of heterogeneous information from various countries confirms the importance of carefully planning any survey of exposure levels which is to yield a statistically useful result.

19. Appropriate measures should be taken to determine more accurately the frequency of each type of examination or treatment. The data available at the present time are particularly scarce or unreliable with regard to the following:

(*a*) Diagnostic examinations by non-radiologists (by radiographic and fluoroscopic methods but particularly by the latter) in countries where these constitute an appreciable part of the total radiological practice.

(*b*) X-ray treatment.

(*c*) Diagnostic and therapeutic uses of internally-administered radioisotopes.

In collecting these data, examinations and treatments should be classified by

(i) radiological type;

(ii) anatomical part;

(iii) age and sex of patient;

(iv) disease (for therapy and radioisotopes, at least).

For (i), (ii) and (iii), the classifications recommended by the ICRP/ICRU Study Group[1] should be used.

20. The classification of examinations suggested by the ICRP/ICRU Joint Study Group[1] has been slightly rearranged, for the purposes of this report, to comprise

1. Hip and femur (upper third)
2. Femur (middle and lower third)
3. Pelvic region
4. Lumbosacral
5. Lumbar spine
6. Dorsal spine
7. Urography (descending [intravenous] pyelography)
8. Retrograde (ascending) pyelography
9. Urethrocystography (bladder examinations, cystography, urethrography)
10. Pelvimetry
11. Hysterosalpingography
12. Obstetrical abdomen
13. Abdomen (pancreas, spleen, liver, pneumoperitoneum, general examinations of the urinary tract)
14. Lower gastrointestinal tract (small intestine, appendix, colon, "barium enema")
15. Upper gastrointestinal tract (pharynx, oesophagus, stomach, "barium swallow and meal")
16. Gall bladder (cholecystography)
17. Chest (heart, cardiac angiography, aorta, respiratory system, lungs)
18. Thorax (sternum, ribs, shoulder, clavicle)
19. Upper limb (hand, forearm, upper arm)
20. Lower leg and foot
21. Head (skull, cervical spine)
22. Dental
23. Mass miniature radiography (photofluoroscopy)

21. For countries where a large part of the radiological work is done in private offices, much of it perhaps by non-radiologists, it is very difficult to determine the total number of examinations per year, and still more difficult to establish the number of examinations of each type or the age and sex distribution of the patients examined. Film consumption provides some check on total volume of radiography, but none at all on fluoroscopy. Under these circumstances it appears that a rather carefully organized survey along the lines suggested by the ICRP/ICRU Study Group is required to obtain the necessary data. It is important to specify whether a total number of examinations, or a figure for film consumption in a country, in fact includes all practices. Special care should be given the presentation of dental and mass chest examinations.

22. For countries where the major part of the diagnostic radiology is controlled by governmental institutions and a high percentage of the examinations is carried out in hospitals, it is probable that the total number of procedures is known fairly accurately and

that sampling of representative hospitals is satisfactory for determining the number of examinations of each type carried out.

23. All information on the number of films, views taken, size of fields and radiographic factors used for an "average" examination are helpful for calculation of dose in the absence of measurements, or as a check on measured values. Measurements performed by specialists give, however, more reliable results than any calculations.

24. The gonad dose per examination should be determined more carefully for those exposure classes in which the doses are expected to have the greatest genetic significance. The dose should be investigated in a manner that permits the assessments of an average for a whole population. The doses received by children require particular attention since few data are available. In any estimates of genetically significant doses, at least children and adults should be treated separately and, when the inaccuracy in other factors has been reduced sufficiently, it may be desirable to classify adults on the basis of size as well.

25. Foetal exposure has a special genetic significance because of the comparatively high relative child-expectancy, which in the case of the foetus becomes W/w (stillborns neglected).

26. The difference between the mean child-expectancy of each class of patients and the mean child-expectancy of the same age and sex group in the population should be determined with regard to its correlation with:

(*a*) type of diagnostic examination;

(*b*) disease treated and type of treatment.

The correlation with type of diagnostic examination may prove to be small but there is at present no evidence. In therapy, the dependence on disease treated is obvious but must be determined quantitatively to permit accurate estimation of the genetically significant dose.

Exposure of the bone marrow

27. According to one hypothesis, the possible radiation induction of leukemia is a linear function of dose. The same dose to different individuals will probably entail different degrees of risk for the subsequent occurrence of the disease, depending upon the age at the time of exposure and other unknown factors. As the appropriate weighting procedure is not known, the various contributions to marrow exposure must, at present, be compared without weighting, and the *per capita* dose in a population is taken as approximately determining the total number of cases of leukemia to be expected during the years following a certain exposure.

28. For the linear dose-effect relationship the relevant dose is assumed to be the mean marrow dose, averaged over the whole mass of active marrow (ca. 1,500 g in an adult). The active marrow is taken to be distributed approximately as follows:

Spinal column	40 per cent
Ribs and sternum	25 " "
Pelvis	15 " "
Skull	10 " "
Other (e.g. in extremities, etc.)	10 " "

Infants and children have a wide distribution of active marrow throughout the skeleton, making estimates of the mean dose difficult, especially as the distribution is dependent on age.

29. According to another hypothesis, there is a threshold dose for the induction of leukemia; in this case a *per capita* marrow dose has no relevance but the individual marrow doses become the determining factors. As the relevant dose may then well be the maximum dose to the marrow, wherever it occurs, the mean dose will not give a measure of the possible risk.

30. As the evaluation of the significance of a marrow exposure may involve the number of "years-at-risk", the mean life-expectancy of each class of patients should be studied.

31. More extensive measurements of the marrow dose resulting from diagnostic and therapeutic procedures should be made.

32. The weight and distribution of active marrow at different ages should be determined.

Diagnostic uses of X-rays

33. It has been estimated that 75 to 90 per cent of the total dose from medical uses of ionizing radiations results from the diagnostic uses of X-rays.[1]

Estimates of the genetically significant dose

34. It should be noticed that almost all estimates of the genetically significant dose from diagnostic exposure have been made under the assumption that the child-expectancy of the patients is not influenced by the nature of the condition for which they were examined. This assumption has not yet been supported by any evidence.

35. The Committee has considered data on gonad exposure from diagnostic X-ray procedures in Australia,[2] Austria,[3] Denmark,[4] England and Wales,[5] France,[6] Japan,[7] Norway,[8] Sweden[9] and U.S.A.[10] Some authors have reported all data needed for an estimate of the genetically significant dose (with the exception stated in paragraph 34), while others have given less complete information. Because of the different procedures of estimates and because of the difference in diagnostic practice, the data are not strictly comparable. However, as far as practicable the material is presented in this report according to the same uniform scheme, following the procedure given in paragraphs 6-26.

36. The material from the various countries is presented separately in appendices 1-10, as it has been found difficult to make a step by step comparison of the data. So far as possible the anatomical classification of examinations recommended by the ICRP/ICRU Study Group[1] has been used. When the original report differs from this classification, the authors' own terms have been used, within quotation marks, following the number of the most closely related standard class. For uniformity of presentation, the data are recorded in terms of equation (8).

37. The procedure by which D_j was estimated for each country is indicated in the introduction to each set of tables. Values of d_j for some of the more important examinations are collected in appendix XI.

38. The most obvious feature of the detailed results has already been pointed out by the ICRP/ICRU Study Group[1] and by others, namely that about 85 per cent of the genetically significant dose results from six or seven anatomical types of examinations (those in the region of the lower abdomen and pelvis), during which the gonads are usually in the primary beam, although these constitute less than 10 per cent of the total number of examinations.

39. Data from countries for which it has been possible to calculate both the *per capita* gonad dose and the genetically significant dose indicate that, at present, these doses are almost the same. This is, of course, a mere coincidence and is true only for the *total* of all contributions. The *relative* contribution from the various exposure classes is quite different in the two cases. For example, while both the annual *per capita* gonad dose and the annual genetically significant dose in the British minimum estimate (see appendix IV) are 23 mrem, the corresponding contributions for an examination of a group with a low child-expectancy such as "female bladder", are 0.26 and 0.08 mrem, and the contributions from a high child-expectancy group such as "foetal exposure in pelvimetry" are 1.4 and 3.4 mrem respectively.

40. Some of the available data have been collected in table I, which gives a comparison of the frequency of examinations and the level of exposure in various countries. The *per capita* number of radiographic examinations reported by Martin in Australia is unusually high and is the main source for the high estimate of the genetically significant dose in this country.

TABLE I. DATA ON GONAD EXPOSURE FROM DIAGNOSTIC X-RAY PROCEDURES IN VARIOUS COUNTRIES

Country	Year of study	Population at time of study (N)	Population under mean age of child bearing (n)	Mean child expectancy (w)	Expected number of children after birth (W)	Relative child expectancy after birth (W/w)	Annual number of examinations per capita of total population: •R Radiography (except dental & mass survey)	•F Fluoroscopy	•M Mass surveys	•D Dental	Consumption of X-ray films—Annual number per capita (f)	Annual genetically significant dose (D_i) (mrem)	$\frac{D_i}{(\bullet R+\bullet F)}$ (mrem)	D_i/f (mrem)	Per capita dose (mrem)
Australia	1955–1957	9,500,000					0.48	—[a]	0.19	no data		160 (28[d])	330 (58[d])		150 (28[d])
Austria	1955–1957	6,974,000	3,095,000			2.25	0.067	0.31	0.0075	no data					16–24
Denmark	1956–1957	4,450,000	(1,610,000)	0.92	2.54	2.76	0.23	—[a]	0.23	no data	1.0	17[d]	75[d]	17[d]	25[d]
England & Wales	1955	44,440,000	(18,700,000)	0.93	2.20	2.36	0.30	—[a]	0.076	0.021		23[d]	75[d]		23[d]
France	1957	42,000,000	19,000,000			2.21	0.15	0.62[c]	0.50[c]	no data	0.86	57[d]	75[d]	65[d]	57[d]
Japan	1956	90,000,000	58,000,000			1.55	0.28	0.04	0.26	no data					10–30
New Zealand	1957	2,221,000	(1,160,000)	1.71	3.28	1.92	0.34	—[a]	0.09	0.24					
Norway	1956	3,400,000							0.15		1.1				
Sweden	1955	7,178,000	(2,980,000)	0.91	2.19	2.41	0.31	—[a]	0.14	(0.3[b])	1.0	38	115	36	
U.S.A.	1955–1956	162,000,000	81,700,000			1.98	0.25	0.08	0.13	0.4 (1.2[b])	0.68	141 (50[d])	430 (150[d])	210 (75[d])	170

[a] Fluoroscopy is generally performed only in connexion with radiography.

[b] Number of films.

[c] 26,000,000 fluoroscopic examinations per year in France include 19,000,000 mass surveys on the population under age 30. In addition, 2,000,000 photofluoroscopic examinations are performed annually, so the total number of mass survey examinations is likely to exceed 21,000,000 per year.

[d] Minimum estimate.

Estimates of bone marrow dose

41. The reports on the dose resulting from the treatment of *Ankylosing Spondylitis* provide the best basis at present for evaluation of a possible risk for radiation-induced leukemia.[11] A discussion on the interpretation of this material is given in chapter V. It should be noticed that some references to marrow dose in literature refer to the mean *spinal* marrow dose instead of the average over the whole mass of active marrow. The latter dose is only about 40 per cent of the mean dose in the spine marrow if other marrow than the spinal has not been exposed.

42. Few measurements of the dose resulting from *diagnostic* X-ray exposure of the bone marrow have been published. The annual mean marrow dose from diagnostic X-ray exposure in Australia has been estimated to be about 100 mrem *per capita*.[12] An attempt has been made here to make another estimate based upon a good current practice and an average frequency of examinations in the same countries which have reported data on gonad exposure.

43. A representative number of examinations of each type N_j, has accordingly been taken from the data on the genetically significant dose, and the mean marrow dose, averaged over the whole active marrow dose, has been calculated from available information on number of films per examination, size of films, skin dose per film, percentage depth dose, etc. Since the estimate at best is only a very preliminary one, it has been considered justifiable to make several simplifying assumptions.

44. All estimates have been based on "standard man" as defined by the ICRP.[13] It has been assumed that the total weight of active marrow is 1,500 grams and that it is distributed as follows: spinal column, 40 per cent; ribs and sternum, 25 per cent; pelvis, 15 per cent; skull, 10 per cent; other, 10 per cent. No estimates for children have been attempted; this would be more difficult because of the wide distribution of active marrow throughout the skeleton of a child and the dependence of this distribution on age.

45. The number of films per examination have been determined from manuals of radiology[14,15] and from published reports on radiographic techniques. The number of films assumed per examination range from one to five (including spot films), depending on the anatomical part; the average is 2.6 as compared with an average of 3 assumed by Laughlin and Pullman.[10] In most cases, Webster and Merrill's[16] values of skin dose have been used. These are considerably lower than many of the published values (e.g. Ritter, Warren and Pendergrass[17]) but are not as low as those of Ardran and Crooks.[18] They are probably fairly representative of the best present-day radiological practice but may be appreciably lower than the skin doses in average practice.

46. The half-value layer of the incident radiation has been assumed to be 3.0 mm of aluminium in all cases, corresponding to an effective voltage of 33.6 kV. The position of the marrow for each view has been determined from "A Cross-Section Anatomy" by Eyclesymer and Schoemaker[19] and the amount of marrow included in the field estimated from reproductions of typical radiographs as found in manuals of radiographic

techniques.[15,16] The percentage depth dose at the level of the marrow has been determined in each case from depth dose tables published by Johns, Epp and Fedoruk,[20] their values being corrected for differences in focus-skin distance and for shielding of marrow by the surrounding bone. The absorption coefficient assumed for bone is not too important since, for the quality of radiation used, the reduction in dose due to bone shielding is probably less than 20 per cent in every case. No correction has been made for the fact that the marrow is located in a trabecular bone structure since it has been estimated[21] that the increase in marrow dose due to proximity of bone is not more than 5 to 15 per cent for radiation of diagnostic quality.

47. The product of the skin dose, the corrected percentage depth dose and the fraction of active marrow assumed to be in the field gives the contribution to the mean marrow dose for each location of marrow. Calculation of dose by this method gives values somewhat lower than measurements of marrow dose reported by Jones and Ellis[21] but are not in serious disagreement. The calulated doses are in good agreement with some preliminary measurements by Laughlin *et al.*[22] of the dose received by the marrow of the vertebral column during a photofluorographic chest examination.

48. The estimates of mean marrow dose from fluoroscopic procedures are much more uncertain than those from radiography. Skin dose rates of 5 r per minute and 10 r per minute have been assumed for radiologists and non-radiologists respectively, and the total time of fluoroscopy taken to be two to five minutes depending on examination. For a country, such as the United States, where the number of examinations by non-radiologists is high, the annual contribution from these examinations to the *per capita* mean marrow dose can be estimated to be between 10 and 20 mrem. In the examinations made by radiologists the fluoroscopic contribution to the *per capita* mean marrow dose is less important although the individual dose from this practice in extreme cases may be very high.

49. From the mean marrow dose, calculated under the simplified assumptions specified above, a *per capita* marrow dose from each type of examination has been estimated, assuming an average frequency of each examination fairly representative for countries such as the United Kingdom, the United States and Sweden. The breakdown of the total by type of examination is given in table II.

50. It is apparent from the table that the highest contribution to the *per capita* mean marrow dose comes from examinations of the gastro-intestinal tract and that mass chest X-ray surveys are of relatively much greater importance here than they are in the case of genetically significant dose. The sum of the contributions in the table is approximately 45 mrem/year and after allowance for the contribution from fluoroscopy, the *per capita* mean marrow dose might be of the order of 50-100 mrem per year, somewhat lower than the Australian estimate[12] and current British estimates[63].

51. The mean marrow dose per examination in mass chest X-ray procedures has been measured by several investigators, who report doses between 70 and 120 mrem

TABLE II. ANNUAL PER CAPITA MEAN MARROW DOSE FROM DIAGNOSTIC X-RAY EXPOSURE (EXCLUDING FLUOROSCOPY)

(Figures based upon an assumed average practice, cf. text)

No.	Examination	Views	*Mean marrow dose (mrem)*	*No. exam. per 1,000 of total pop.*	*Annual per capita marrow dose (mrem)*
1.	Lower femur	1 AP + 1 LAT	5	5	0.025
2.	Hip and femur	1 AP + 1 LAT	30	5	0.15
3.	Pelvis	1 AP	20	5	0.1
4.	Lumbo-sacral	1 AP + 1 LAT + 2 OBL	300	5	1.5
5.	Lumbar spine	1 AP + 2 LAT	400	5	2.0
6.	Dorsal spine	1 AP + 1 LAT + 1 OBL	400	5	2.0
7.	Intrav. pyelography	5 AP	200	5	1.0
8.	Retrog. pyelography	2 AP	100	2	0.2
9.	Urethrocystography	1 AP + 1 LAT + 2 OBL	300	1	0.3
10.	Pelvimetry	1 AP + 1 outlet + 2 LAT	800	0.5	0.4
11.	Salpingography	3 AP	100	0.2	0.02
12.	Abdomen (obstetrical)	1 AP	100	0.5	0.05
13.	Abdomen	1 AP	50	5	0.25
14.	Lower G.I.	2 AP + 3 PA	700	10	7.0
15.	Upper G.I.	1 AP + 2 PA + 1 LAT	500	20	10
16.	Cholecystography	4 PA	400	5	2.0
17.	Chest	1 PA + 1 LAT	40	80	3.2
18.	(*a*) Ribs and sternum.	1 PA + 1 LAT	200	2	0.4
	(*b*) Shoulder	1 PA + 1 LAT	20	5	0.1
19.	Arm	1	2	30	0.06
20.	Foot	1	2	30	0.06
21.	(*a*) Skull	1 AP + 1 PA + 2 LAT	50	30	1.5
	(*b*) Cervical spine	1 AP + 1 PA + 2 LAT	50	5	0.25
22.	Dental	1	20	100	2.0[a]
23.	Mass min.[b]	1 PA	100	100	10

[a] American practice including about 400 examinations per year per 1,000 of total population gives a mean marrow dose of 8 mrem *per capita* and year. British practice involves only 20 examinations per year per 1,000 of total population, which corresponds to less than 0.4 mrem *per capita* and year. The assumptions on location of active marrow make estimates for skull exposure very uncertain.

[b] See discussion in text, paragraphs 51–52.

for good practice, with examinations involving only a postero-anterior view.[12,22,23,63] In some countries lateral views are taken in addition to the postero-anterior view.[23] Although the doses reported per examination might be considered as low estimates for the current practice, there are indications that it may be possible to reduce this exposure considerably in the future.

52. The relatively high *per capita* mean marrow dose from mass chest X-ray examinations is due to the high frequency of this examination. Assuming 10 per cent of the population examined each year the annual *per capita* mean marrow dose from this type of examination would be 10 mrem; however, certain regions report as high frequency as one examination *per capita* per year which would result in the ten-fold *per capita* dose.

53. In countries where fluoroscopy has not been replaced by photofluoroscopy for mass surveys,[6] the annual *per capita* mean marrow dose probably results to a high degree from these surveys and may considerably exceed 100 mrem.

Accuracy of estimates

54. The Committee is in agreement with the suggestion of the ICRP/ICRU Study Group[1] that since the accuracy in estimating the annual genetically significant dose to a "normal" population due to natural sources is about ± 25 mrem, the same absolute accuracy is satisfactory for a first estimate, at least, of the genetically significant dose due to medical sources. This means an accuracy of ± 25 per cent for e.g. the United States and about ± 100 per cent for countries such as Denmark and Sweden. It is stated by Osborn and Smith[5] that the estimate for the United Kingdom may be out by a factor of 2 to 10 and there is a factor of nearly 3 between the minimum and probable doses estimated for the United States.[10] It is evident that the accuracy desired for even a first estimate has not yet been obtained: the eventual objective should be to reduce the absolute uncertainty of the estimate well below that of the background dose.

55. It is convenient to discuss the inaccuracies in the estimates which have been made of the genetically significant dose in terms of equation (8). As pointed out in paragraphs 21-22, the total number of examinations is not very accurately known in countries where a large part of the radiological work is done in private offices and even by non-radiologists.

56. Estimation of the factor w_j/w in equation (8) depends, as has already been said, on two considerations: (*a*) the age and sex distribution of patients receiving each type of examination and (*b*) the difference between the child-bearing expectancies of class jk and class k as a whole. There does not appear to be any evidence on the latter point. However, for most types of diagnostic examination w_{jk} may not differ greatly from w_k. Further, it is only for the six or seven examinations which make the largest contributions that a difference between w_{jk} and w_k can affect appreciably the estimate of genetically significant dose.

57. The determination of the distribution of the total number of examinations on various exposure classes and on age and sex groups must be made by sampling procedures. This is difficult to carry out satisfactorily unless a high percentage of the examinations are made out at a relatively small number of hospitals.

58. The same difficulty is related to the estimate of a representative average gonad dose per examination. As the gonad dose per examination varies from hospital to hospital it is very difficult to give an average with a good accuracy. This is probably the main source of uncertainty to the calculated genetically significant dose and the *per capita* mean marrow dose. Values of the gonad dose per examination as measured in various countries are collected by type of examination in appendix XI.

59. Another source of uncertainty in the *per capita* mean marrow dose is the scant information on the distribution of active marrow.

Reduction of gonadal dose

60. From an international point of view, the most serious criticism is the fact that to date, estimates are available for only six or seven countries. Fortunately, the have been made for some of the countries in which medical exposures may be expected to be highest.

61. It has been demonstrated[1,9,13,16,18,22,24-36,61] that gonad doses can be reduced very decidedly by improved techniques (e.g., by a factor of 50 to 100) for some examinations of males. The greatest attention must be paid, of course, to the six or seven examinations which contribute the largest significant doses. Methods have been pointed out by the ICRP.[1,13]

62. The following is quoted from the report of the ICRP/ICRU Joint Study Group:[1]

"1. *Current Recommendations*

"*Equipment for fluoroscopy*

"The fixed total filter equivalent value should be at least 2 mm aluminium, and should be based on the value obtained at the highest voltage of the X-ray apparatus.

"The use of a timer to measure the fluoroscopy time is recommended.

"*Procedure for fluoroscopy*

"Before a fluoroscopic examination is begun, the eyes must be sufficiently dark-adapted. In order to work with the lowest possible dose-rate, the adaptation period should be at least 10 minutes. A smaller time may be used if there has been preliminary adaptation using red goggles.

"*Equipment for radiography*

"A total filter of at least 2 mm aluminium should be used.

"An automatic switch should be incorporated.

"*Other types of diagnostic work*

"*Dental radiography*

"Fluoroscopy is strongly deprecated.

"*Mobile diagnostic equipment*

"All transportable equipment should be provided with cones or with other restricting devices so that the smallest anode skin distance is normally at least 30 cm (12 in.).

"It should be noted that damage has occurred to workers and patients from contact radiography.

"At least 1.5 mm aluminium equivalent should be provided as a fixed total filter.

"Fluoroscopy should be used only if the equipment meets the requirements recommended for fluoroscopic equipment.

"*Protection of patients*

"*General rules*

"By X-ray protection of the patient it is meant that the radiation exposure of the patient should be reduced as much as is compatible with successful diag-

nostic investigation or therapeutic treatment. In the case of non-malignant diseases, therapeutic treatment shall be employed with caution. In all therapeutic and diagnostic exposures, the integral dose should be kept as low as possible in order to protect the patient as much as possible from the radiation. Moreover, for this purpose, the tube-current, or the mAs value, and the number of examinations should be kept to a minimum. An automatic timer should indicate the length of the diagnostic or therapeutic exposure. In all diagnostic investigations, the beam that strikes the patient should have a cross-section no larger than is essential for the investigation. This is of particular importance in fluoroscopy. In all irradiations the gonads should be protected as much as possible by collimation of the beam or by protective screens. In the case of children, it is important, in view of the little known action of radiation on growing tissues, to be cautious about repeating diagnostic examinations and to avoid too frequent systematic examinations of the whole of the body.

"*Exposure in diagnostic examinations*

"For ease and clarity in the consideration of exposures received in diagnostic work, it is recommended that tables be set up giving doses for radiography and fluoroscopy of lung, stomach, intestines, etc. Integral dose should also be taken into account as it gives a much clearer picture of the true exposure. Special attention should be given to the possible hazards to pneumothorax patients who, as a result of the many screenings after each inflation, may receive large doses. The screenings should be replaced in part by radiographs.

"*Radiation certificate*

"In view of the continually increasing medical and technical use of ionizing radiation, it is desirable to accumulate information regarding the doses received both by individuals and by the population as a whole. As far as the individual is concerned, the information could be obtained by the introduction of a certificate in which are recorded details of all radiation exposure (medical and occupational) received through life. Probably it is impracticable to introduce such a certificate at present, but it is recommended that all radiologists and dentists keep records of the doses given, and the field sizes and radiation qualities used, in all diagnostic procedures. (It is presumed that such records are already available in the case of therapeutic procedures.)

"2. *Recommendations regarding the following items are under consideration*

"(*a*) The provision of specially designed protective devices for the gonads of patients.

"(*b*) Additional recommendations regarding minimum film-focus distances.

"(*c*) Increasing the protective requirements for diagnostic and therapeutic tube housings.

"(*d*) Improvements in beam collimation.

"(*e*) The provision of permanent filters of at least 2 mm Al equivalent on all diagnostic X-ray tubes.

"(*f*) The advantages of using high voltage techniques for diagnostic work.

"(*g*) The provision of exposure counters on all diagnostic equipment.

"(*h*) The use of image intensifiers to reduce the dose to the patient, and consequently to the operator, rather than as a means of permitting more extensive and prolonged fluoroscopy than hitherto."

63. It is improbable that there will be great improvement in accuracy of estimation of gonad doses until the range of actual doses is reduced appreciably by conscientious adherence to procedures as have been recommended by the ICRP. In this connexion it is probable that the "feedback" suggested by the ICRP/ICRU Study Group is already operating, i.e., the attention to estimation of the genetically significant dose is already reducing the dose.

64. Reduction of gonad dose may also be obtained in the future by means of improved radiological equipment and supplies, e.g., faster films, faster screens, etc. The advantage to be gained by increased use of image amplifiers has already been pointed out by the ICRP/ICRU.[1]

65. Finally, reduction in gonad dose can be achieved by a reconsideration by the medical profession of the circumstances under which X-ray diagnosis is appropriate. This could be facilitated by statistical information on the significance of each examination class for the reduction of any specified morbidity. When medical decision has been taken, administrative co-ordination should be improved between authorities who require that certain examinations be made in the routine health surveillance of whole populations or special groups such as school-children, students, employees, immigrants.

66. The tables in appendix XI point to the possibility of carrying out some examinations at much lower gonad exposure levels than are likely to be obtained in the average case at present. The annual genetically significant dose that may be achievable without detriment to diagnostic information has been estimated to be less than 30 mrem for Australia[2] and 15 mrem for Sweden.[9]

Radiotherapy

Genetically significant dose

67. S. H. Clark[37] has estimated the genetically significant dose due to radiotherapy in the United States as about 10 mrem per year. This figure, quoted by Laughlin and Pullman,[10] is based on the assumption that treatment of malignant conditions are not genetically significant. It may hence be an under-estimate. For Australia, Martin[2,36] reports an estimate of the contribution to the genetically significant dose from radiotherapy as 28 mrem per year, assuming a normal child-expectancy of all surviving patients that were not assumed to be sterilized by the irradiation. Survey by Purser and Quist[38] yields an estimate of 1 mrem *per capita* gonad dose per year in Denmark. In the Danish survey it was found that 22 per cent of the genetically significant dose resulted from treatment of malignant conditions, assuming that the patients treated for malignancies have one-fifth the child-expectancy of normal individuals.

Bone marrow dose

68. It does not appear possible to estimate with any certainty even the order of magnitude of the *per capita* mean marrow dose, due to radiotherapy, from the data at present available to the Committee.

Internally administered radioisotopes

69. The principal contributions to the population dose from the medical use of radioisotopes arise from the use of I^{131} and P^{32} which are most widely employed. While considerable quantities of Au^{198} are used, the biological significance of exposure from this course is negligible

since Au^{198} is generally limited to palliative treatment of incurable conditions. Other radioisotopes are used in very small quantities and almost entirely for diagnostic purposes.

70. Estimates of the *per capita* gonad dose resulting from the use of I^{131} and P^{32} can be based upon information about either treatments or radioisotope shipments, the first approach being more accurate and preferable.[37,39,40] From the report of the ICRP/ICRU Joint Study Group[1] and other information available to the Committee,[39,40] it seems likely that the genetically significant dose is lower than 1 mrem per year, even in the countries for which the highest figures can be expected.

71. Some experience on the effects of ingesting radioactive substances relates to the early period when the hazard was not realized. The work with radioactive luminous materials was early recognized as hazardous if not properly conducted,[41] but radioactive contrast media such as Thorotrast were being used occasionally in X-ray diagnostic work until a few years ago. The high retention of the radioactive material in the liver and the spleen resulted in rather high exposure, with dose-rates of the order of 0.3 rem per day during periods of years.[42,43]

III. Industrial and research uses of X-rays and radioactive materials

Occupational exposure

72. The exposure from industrial and research uses of X-rays and radioactive materials is mainly an occupational one. The extent to which non-occupationally exposed individuals are exposed depends upon the degree of environmental contamination. The latter problem is treated in annex D.

Medical workers

73. The countries reporting on the number of persons in medical radiological work[3,7,10,44–46] have presented figures ranging from 0.17—0.69 per 1,000 of the total population. However, in many cases it is not clear what has been meant by "medical worker".

74. The following table shows the extent of X-ray work in New Zealand[45] and Sweden[47] and gives an idea of the relative number of various installations in countries with extensive medical facilities.

Table III. Number of X-ray installations

Type of installation	New Zealand, 1957: Number of plants per 1,000 of total population	Sweden, 1955: Number of plants per 1,000 of total population	Sweden, 1955: Number of exposed workers per 1,000 of total population
Diagnostic	0.14	0.15	0.46
Therapy	0.02	0.01	0.03
Dental	0.24	0.40	0.93
Chiropractors and naturopathic	0.02	—	—
TOTAL MEDICAL	0.42	0.56	1.42
Shoefitting	0.03	—	—
Veterinary	0.01	0.004	0.01
Industrial	0.003	0.02	0.06
Research and educational	0.01	0.03	0.02

75. The age-distribution of the workers is usually such that about 50 per cent are under the mean age of child-bearing.[3,7,46] Hence, the genetically significant dose is approximately equal to the *per capita* dose. Average annual doses ranging from 500 - 5,000 mrem have been reported to the Committee as resulting from occupational medical exposure,[3,7,44–46] but this exposure does not refer to all installations shown in table III. For example, the exposure of dentists or their assistants is usually very small,[47] and most radiotherapy with X-rays can be carried out under conditions ensuring good protection of the personnel.[48] Annual average doses of up to 5,000 mrem refer to less than 0.2 persons per 1,000 of the total population and result therefore in a *per capita* dose of less than 1 mrem per year, mostly from X-ray diagnostic work.[48,49]

76. Medical radioisotope work is usually performed with little exposure of the personnel.[48] An important exception is the work with implantation of radium applicators and needles where the personnel may at present be exposed to considerably more than 100 mrem per week.[50,66,67] This exposure, however, involves only a very small group of people.

Atomic energy workers

77. More complete and more accurate data are available for this group than for any other occupationally exposed group, since in countries in which atomic energy establishments are operated, monitoring procedures have been set up to cover exposed personnel.

78. The contribution from exposure of atomic energy workers to the genetically significant dose to the population is about 0.1 mrem per year or less in countries for which it has been estimated.[44,46,51,52] However, since the number of atomic energy workers is expected to increase in the near future, this figure may increase in proportion.

79. The figures in table IV have been taken from a report of the United States Atomic Energy Commission.[51]

Table IV. Exposure of atomic energy personnel in the United States of America

(a) *Exposure of A.E.C. contractor personnel to penetrating radiation (1955)*

Annual dose (mrem)	Number of workers	Percentage
0– 1,000	56,708	94.2
1,000– 5,000	3,157	5.2
5,000–10,000	285	0.5
10,000–15,000	41	<0.1
>15,000	3	<0.01
	60,194	100.0

(b) *Highest accumulated yearly doses to individual A.E.C. contractor employees during routine operations (accidents excluded)*

Year	Highest dose (rem)	Average of 10 highest doses (rem)
1947	23.5	5.2
1948	20.3	4.2
1949	13.6	2.6
1950	9.0	2.2
1951	7.1	1.8
1952	15.7	2.9
1953	12.9	3.4
1954	27.8	3.9
1955	17.9	4.1

Industrial and research workers

80. The information on exposure of industrial and research workers is less complete than the information on exposure of the other occupational groups.[3,44–46,48,53] As is evident from the relation between the number of persons and number of plants in table III, the concept "research worker" is not well defined. If the exposure is assumed to be equal to that in the group of medical workers, the contribution to the population dose is lower, because of the smaller number of workers. Industrial γ-radiography is one of the main sources of exposure of this group.[48]

81. A special occupational problem is the exposure of workers in mining and milling radioactive materials such as uranium.[48,54] If not properly conducted, this work may involve considerable hazard to the workers.

Summary

82. From the information surveyed above, it appears that the contribution from occupational exposure to the genetically significant dose is less than 2 mrem per year for most countries. Despite the fact that this contribution is relatively small and the corresponding contribution to doses significant for somatic injury is also small, the exposure of radiation workers merits special attention for two reasons: (*a*) there will be a considerable increase in the near future in the number of atomic energy employees in many countries, and (*b*) individual exposures may be high even though the contribution to the mean dose of the population is small.

83. Methods for reducing the occupational exposure have been pointed out by ICRP[13] and ILO.[55]

IV. Other man-made sources of radiation

84. Watches and clocks with radioactive luminous dials give an annual genetically significant dose of about 1 mrem.[46,56] X-rays from television receivers contribute less than 1 mrem.[46] X-rays from shoe-fitting fluoroscopes contribute still less, as they normally expose a relatively small number of individuals.[45,46,57] (However, they might be an important hazard to the exposed individuals, see reference 64.)

Appendices

DATA FOR EVALUATION OF THE GENETICALLY SIGNIFICANT DOSE FROM DIAGNOSTIC X-RAY EXPOSURE

Appendix I

AUSTRALIA

The data on gonad exposure in Australia have been taken from papers by Martin[2,36]. The author has rearranged his material for the purpose of this report. Martin's estimate of the annual genetically significant dose is unusually high. This is mainly due to the high *per capita* number of examinations, which the author has assumed to be 60 per cent higher than the number for England and Wales (cf. paragraph 40).

(*See Appendix I. Table I on page 71.*)

Data for evaluation of the genetically significant dose from diagnostic X-ray exposure

Appendix I. Table I. Australia

No.	Examination	Females <30 d_j^* (mrem)	Females <30 1,000 N_{jk}^*/N	Females <30 w_{jk}^*/w	Females <30 D_{jk}^* (mrem)	Females 30–44 1,000 N_{jk}^*/N	Females 30–44 w_{jk}^*/w	Females 30–44 D_{jk}^* (mrem)	Females >44 1,000 N_{jk}^*/N	Females >44 w_{jk}^*/w	Females >44 D_{jk}^* (mrem)	Males <30 d_j^* (mrem)	Males <30 1,000 N_{jk}^*/N	Males <30 w_{jk}^*/w	Males <30 D_{jk}^* (mrem)	Males 30–44 1,000 N_{jk}^*/N	Males 30–44 w_{jk}^*/w	Males 30–44 D_{jk}^* (mrem)	Males 44> 1,000 N_{jk}^*/N	Males 44> w_{jk}^*/w	Males 44> D_{jk}^* (mrem)	TOTAL D_j (mrem)	TOTAL Per cent
1.	"Hips"	440	1.94	3.05	2.61	1.34	0.25	0.15	3.48	0.003	0.0046	880	1.97	2.76	4.8	1.24	0.58	0.63	2.42	0.003	0.0061	8.2	10.8
2.																							
3.	"Pelvis"	800	1.7	"	4.15	1.17	"	0.235	3.04	"	0.0007	1,080	1.9	"	5.66	1.19	"	0.749	2.34	"	0.007	10.8	14.2
4.	"L. S. J."	1,025	2.06	"	6.45	1.42	"	0.364	3.68	"	0.0113	81	3.28	"	0.734	2.06	"	0.097	4.03	"	0.001	7.7	10.1
5.																							
6.	"D. Vert"	124	1.27	"	4.82	0.87	"	0.27	2.27	"	0.0084	17.2	1.75	"	0.083	1.1	"	0.011	2.15	"	0.0001	5.2	6.8
7.	"I. V. P."	1,360	1.4	"	5.83	0.96	"	0.328	2.5	"	0.0102	590	1.68	"	2.73	1.05	"	0.36	2.06	"	0.0037	9.3	12.2
8.	"Ret. Pyel."	800	0.3	"	0.73	0.21	"	0.042	0.54	"	0.0013	700	0.29	"	0.56	0.18	"	0.073	0.35	"	0.0007	1.4	1.8
9.	"Bladder"	210	0.18	"	0.115	0.12	"	0.0063	0.32	"	0.0002	240	0.44	"	0.29	0.28	"	0.0383	0.54	"	0.0004	0.45	0.6
10.																							
11.	"Salpine"	25,000	0.12	"	9.15	0.08	"	0.5	0.21	"	0.016	—	—	—	—	—	—	—	—	—	—	9.7	12.7
12.																							
13.	"Ur. tract"	203	2.9	"	1.795	2	"	0.101	5.19	"	0.00315	110	4.01	2.76	1.22	2 52	0.58	0.161	4.93	0.003	0.0016		
	"Kidney"	60	0.12	"	0.0021	0.08	"	0.0001	0.21	"	—	3.7	0.15	"	0.0014	0.09	"	0.0002	0.18	"	—		
	"Liver"	20	0.06	"	0.0037	0.4	"	0.0002	0.11	"	—	2.0	0.07	"	0.0003	0.04	"	0.0001	0.09	"	—	3.3	4.3
14.	"Intest. Tract"	520	1.45	"	2.3	1	"	0.13	2.6	"	0.0041	130	1.82	"	0.651	1.14	"	0.086	2.24	"	0.0009	3.2	4.2
15.	"Stomach"	360	3.27	"	3.59	2.26	"	0.203	5.85	"	0.0063	470	6.05	"	7.84	3.8	"	1.04	7.43	"	0.010	12.7	16.7
16.	"Gall Bladder"	70	2.78	"	0.591	1.92	"	0.0335	4.97	"	0.001	2.7	1.39	"	0.0105	0.87	"	0.0014	1.71	"	—	4.0	5.2
	"Cholecyst."	378	2.76	"	3.17	1.9	"	0.179	4.94	"	0.0056	13.5	1.01	"	0.0375	0.64	"	0.005	1.24	"	—		
17.	"Chest"	2.4	17.6	"	0.1285	12.1	"	0.0073	31.4	"	0.0023	0.4	15.2	"	0.0168	9.55	"	0.0022	18.7	"	—	0.2	0.2
18.	"Ribs"	3.8	0.49	"	0.0055	0.34	"	0.0003	0.88	"	—	0.7	0.37	"	0.0008	0.23	"	0.0001	0.45	"	—		
	"Shoulder"	3.4	0.91	"	0.0095	0.63	"	0.0005	1.63	"	—	0.7	1.75	"	0.0033	1.1	"	0.0005	2.15	"	—	0.02	0.03
19.	"Extrem."	1.0	10.6	"	0.0324	7.3	"	0.0018	19	"	—	2.1	19.6	"	0.113	12.3	"	0.015	24.1	"	0.0002	0.2	0.2
20.																							
21.	"Skulls, etc."	1.0	7.5	"	0.0229	5.4	"	0.0013	13.4	"	0.0004	0.2	9.2	"	0.005	5.77	"	0.007	11.3	"	0.0001	0.05	0.06
	"C. Vert."	1.2	1.03	"	0.0037	0.71	"	0.0002	1.84	"	—	1.5	1.09	"	0.0044	0.68	"	0.0006	1.34	"	—		
22.																							
23.																							

			100
Sub-total:	Adult examinations	76	47
	Children	46	28.4
	Foetus	22.6	14.0
	Fluoroscopy	17	10.5
	Mass surveys	0.2	0.1
	Total	162	100.0

APPENDIX II
AUSTRIA

The data submitted by Austria[3] do not permit a presentation according to Equation (8). The following information is given:

Type of examination	1,000 N_j/N	d_j (mrem) Females	d_j (mrem) Males
(A) *Radiography:*			
Pelvis, hips, lumbar spine	6	40–240 (AP) 20–80 (Lat)	6–24 (AP) 8–30 (Lat)
Abdomen, colon, genito-urinary	7.5	6,000	12,000
Pelvimetry, obstetrics	0.75	200 (AP) 1,000 (Lat)	—
Other classic techniques	52	60	40
Tomography	0.15	2	2
Other special techniques	0.75	—	—
Dental	not known	10–100	10–100
Mass surveys	7.5	2	1
(B) *Fluoroscopy:*			
Mass surveys	negligible	—	—
Other examinations	310	not known	not known

From the above data, the *per capita* gonad dose from diagnostic X-ray exposure is estimated to be 16-25 mrem per year.

APPENDIX III
DENMARK

The primary material

1. The following estimate of the genetically significant dose from diagnostic X-ray procedures in Denmark is based upon data published by Hammer-Jacobsen.[4] The author assumes the annual number of examinations in Denmark to be 1,000,000 plus 1,000,000 mass chest photofluoroscopies. The data are assumed to be representative for 1956 (the dose-measurements were made during September 1956-February 1957).

2. The examinations cover the total practice with radiography and fluoroscopy combined. However, the distribution of examinations with respect to type and sex is as observed in one hospital in which about 5 per cent of the total number of examinations are performed.

3. The author estimates a *per capita* dose of 26 mrem from the above data, but considers that this may be a minimum estimate.

4. No data on foetal exposure are given. The author estimates the foetal contribution to the total *per capita* dose in proportion to the relation foetal/female contribution given by Osborn and Smith.[5]

Presentation of the material for this report

5. The Danish data include values for N_j and d_j in all cases needed for an estimate of D_j.

6. No values for w_j/w are given. The values for w_j/w presented in the table for England and Wales have been used as substitutes in the first approximation. This gives female and male contributions of 5 and 8 mrem to the genetically significant dose, as compared to the author's *per capita* doses of 7 and 15 mrem respectively.

7. If the foetal contribution is taken in proportion to the female contribution and the ratio 72.2 per cent from the British report is used, the foetal value will be 4 mrem. This seems, however, to be a low value, as a back calculation by help of the known value of w_j/w for the foetus, implies a foetal dose of, e.g., less than 500 mrem per examination from pelvimetry, whereas other countries report values ranging from 2,500-4,500 mrem.

DATA FOR EVALUATION OF THE GENETICALLY SIGNIFICANT DOSE FROM DIAGNOSTIC X-RAY EXPOSURE

APPENDIX III. TABLE I. DENMARK

No.	Type of examination	Females 1,000 N_j/N	Females d_j mrem	Females w_j/w	Females D_j mrem	Males 1,000 N_j/N	Males d_j mrem	Males w_j/w	Males D_j mrem	Totals D_j mrem	Totals D_j per cent
1.	Hip and femur	2.5	54	0.7	0.09	2.2	911	1.1	2.20	2.29	13.4
2.	"Knee and crus"	4.7	0.6	0.7	0.00	4.3	3.25	1.1	0.02	0.02	0.1
3.	Pelvic region	0.7	195	0.9	0.13	2.5	527	0.6	0.79	0.92	5.4
4.–5.	Lumbar spine	3.4	206	0.6	0.42	4.3	97	0.8	0.33	0.75	4.4
6.	Dorsal spine	1.1	14	0.7	0.01	2.2	20	0.8	0.04	0.05	0.3
7.	Intraven. pyelography	4.3	525	0.8	1.81	4.3	948	0.5	2.04	3.85	22.5
8.	Retrograde pyelography	0.4	1,060	0.8	0.34	0.9	2,400	0.5	1.08	1.42	8.3
9.	"Urethrocystography"	0.0	430	—	0.00	0.4	3,450[a]	0.5	0.69	0.69	4.0
	"Cystogr. dur. micturition"	0.4	406	0.3	0.04	0.4	4,720	0.23	0.43	0.45	2.6
10.	Pelvimetry	2.2	764	0.9	1.51	—	—	—	—	1.51	8.8
11.	Hysterosalpingography	0.9	183	1.1	0.18	—	—	—	—	0.18	1.1
12.	Obstetrical abdomen	2.0	177	1.8	0.64	—	—	—	—	0.64	3.7
13.	"Abdomen, A. P., urin."	0.4	79	0.6	0.02	0.4	567	0.6	0.14	0.16	0.9
14.	"Barium enema"	4.3	19	0.2	0.02	4.3	37	0.4	0.06	0.08	0.5
15.	"Barium swallow and meal"	7.2	8.4	0.4	0.02	7.4	19	0.04	0.06	0.08	0.5
16.	"Gall bladder"	4.0	14.5	0.2	0.01	2.0	1.7	0.3	0.00	0.01	0.1
17.	"Chest"	36.0	0.07	1.3	0.00	34.6	0.33	1.3	0.01	0.01	0.1
	"Chest, special"	3.8	5.0	0.5	0.01	4.5	34	0.8	0.12	0.13	0.8
18.	"Shoulder"	2.0	0.03	0.7	0.00	2.2	0.20	0.9	0.00	0.00	0.0
	"Ribs and sternum"	0.2	0.15	0.4	0.00	0.4	0.45	0.7	0.00	0.00	0.0
19.	"Arm and hand"	5.8	0.05	1.1	0.00	9.4	0.24	1.5	0.00	0.00	0.0
20.	"Foot"	2.9	0.6	1.0	0.00	4.7	3.25	1.2	0.02	0.02	0.1
21.	"Head"	14.8	0.2	1.5	0.00	17.5	0.8	1.6	0.02	0.02	0.1
	"Teeth"	1.3	0.8	1.0	0.00	1.8	4.4	0.9	0.01	0.01	0.1
	"Cervical spine"	4.0	0.17	0.5	0.00	3.8	1.6	1.1	0.01	0.01	0.1
22.	Dental	—	—	0.5	0.00	—	—	0.4	—	0.00	0.0
23.	Mass min. radiography	110	0.15	1.3	0.02	110	0.25	0.9	0.02	0.04	0.2
	SUB-TOTALS	—	—	—	5.25	—	—	—	8.09	13.3	—
	Allowance for foetal exposure, assumed to be 72.2% of female contribution									3.8	22.4
									TOTAL	17	100

[a] The dose 3,450 mrem for males in item 9 is an average of dose measurements from 7 male adults urethrography + 1 boy urethrography + 2 male adults cystography.

APPENDIX IV

ENGLAND AND WALES

The primary material

1. The Committee has not received material upon which it can base an estimate of the probable genetically significant dose for England and Wales. It is, however, possible to give a lower limit under certain assumptions. The primary figures (for radiography and fluoroscopy combined) have been taken from a report by Osborn and Smith (1956).[5] These authors have used values for the gonad dose per examination published by Stanford and Vance (1956).[58] They computed the product $N_j^* w_j^* d_j^*$ using the following statistics:

(*a*) The total number of diagnostic examinations per year based on official figures.

(*b*) The distribution of examination with respect to type, age and sex in what was believed to be a representative sample of hospitals.

(*c*) The child-expectancy derived from official statistics and assumed not to be influenced by the nature of the condition for which the patient was examined (except in the case of hysterosalpingography).

2. An extensive British survey of the diagnostic exposure in the United Kingdom is at present being made,[59] but no data are available for this report.

*Presentation of the material for this report**

3. After division by wN the values reported by Osborn and Smith may be taken as approximate lower limits of the contributions to the genetically significant dose for England and Wales. The values of w_j/w for each examination class have been calculated from the known values of N_j/N, d_j and the approximation of D_j, and should depend only upon the age-distribution within the class following the assumption under 1. (*c*) above.

* These calculations are based on available figures which in some cases have been "rounded off" in publication. The results are therefore approximate and, although adequate for the present purpose, are less accurate than could be derived from calculations based on the original data.

NUMBER OF EXAMINATIONS PER 1,000 OF TOTAL POPULATION
(1000 N_j^*/N)

APPENDIX IV. TABLE I. ENGLAND AND WALES

Exam. No.	*Females (all ages)*	*Males (all ages)*	*Foetal gonads*
1.			
2. "Hip and femur"	5.6	5.6	0.03
3. Pelvis	2.8	2.8	0.09
4.			
5. "Lumbar spine"	5.6	5.6	0.10
6. "Thoracic spine"	2.4	2.0	0.04
7.			
8. "Pyelography"	2.4	2.8	0.07
9. "Bladder"	0.4	0.4	0.014
10. Pelvimetry	0.58	—	0.58
11. Salpingography	0.14	—	—
12.			
13. "Abdomen with obstetric"	4.4[a]	2.4	2.15[b]
14. "Barium enema"	2.8	2.0	0.02
15. "Barium swallow and meal"	6.4	10.4	0.11
16. Cholecystography	1.6	0.8	0.02
17. Chest	50[c] + 3.2[d]	47[c] + 1.6[d]	1.2[c] + 0.24[d]
18. "Ribs and sternum + shoulder"	0.4 + 2.4	1.6 + 3.2	0.00 + 0.00
19. Arm	17.1	19.1	0.20
20. Lower leg	15.6	20.0	0.17
21. "Head + cervical spine"	13.6 + 2.8	15.4 + 1.6	0.25 + 0.00
22. Dental	11.9 + 1.2[e]	7.2 + 0.8[e]	0.14
23. Mass surveys	30.2	46	
24. Others	0.8	16.3	

[a] Including 1.94 obstetrical.
[b] Including allowance for possible pregnancy in non-obstetric abdominal examinations.
[c] Large film.
[d] Special film.
[e] Teeth exam. at hospitals.

Relative child expectancy
(w_j^*/w)

Appendix IV. Table II. England and Wales

Exam. No.	Females (all ages)	Males (all ages)	Foetal gonads
1.			
2. "Hip and femur"	0.75	1.13	2.36
3. Pelvis	0.93	0.56	"
4.			
5. "Lumbar spine"	0.63	0.83	"
6. "Thoracic spine"	0.67	0.80	"
7.			
8. "Pyelography"	0.81	0.53	"
9. "Bladder"	0.30	0.23	"
10. Pelvimetry	0.94	—	"
11. Salpingography	1.07	—	—
12.			
13. "Abdomen with obstetric"	1.08	1.54	2.36
14. "Barium enema"	0.22	0.58	"
15. "Barium swallow and meal"	0.40	0.43	"
16. Cholecystography	0.16	0.28	"
17. Chest	1.3/0.50	1.3/0.85	"
18. "Ribs and sternum + shoulder"	0.38/0.67	0.74/0.88	"
19. Arm	1.1	1.5	"
20. Lower Leg	0.98	1.2	"
21. "Head + cervical spine"	1.5/0.52	1.6/1.1	"
22. Dental	0.53/1.0	0.37/0.87	"
23. Mass surveys	1.32	0.88	"
24. Others			

(See footnotes to table I).

Gonad dose per examination
(d_j^* in mrad or mrem)

Appendix IV. Table III. England and Wales

Exam. No.	Females (all ages)	Males (all ages)	Foetal gonads
1.			
2. "Hip and femur"	195	660	744
3. Pelvis	195	1,020	744
4.			
5. "Lumbar spine"	663	120	663
6. "Thoracic spine"	14	20	14
7.			
8. "Pyelography"	1,200	452	2,990
9. "Bladder"	642	260	2,430
10. Pelvimetry	1,190	—	2,490
11. Salpingography	1,580	—	—
12.			
13. "Abdomen with obstetric"	186	64	539
14. "Barium enema"	18.6	37	18.6
15. "Barium swallow and meal"	8.4	18.6	8.4
16. Cholecystography	14.5	1.7	14.5
17. Chest	0.065/5.0	0.33/34	0.065/5.0
18. "Ribs and sternum + shoulder"	0.15 /0.03	0.45/ 0.20	0.15 /0.03
19. Arm	0.05	0.24	0.05
20. Lower leg	0.56	3.3	0.56
21. "Head + cervical spine"	0.2 /0.17	0.74/ 1.6	0.2 /0.17
22. Dental	0.74	4.4	0.74
23. Mass surveys	0.14	0.23	0.14
24. Others			

(See footnotes to table I).

ANNUAL GENETICALLY SIGNIFICANT DOSE
(D_j in mrem)

APPENDIX IV. TABLE IV. ENGLAND AND WALES

Exam. No.	*Females (all ages)*	*Males (all ages)*	*Foetal*	*Total*	*Per cent of total*
1.					
2. "Hip and femur"	0.82	4.18	0.05	5.05	21.8
3. Pelvis	0.51	1.60	0.16	2.27	9.8
4.					
5. "Lumbar spine"	2.34	0.56	0.16	3.06	13.2
6. "Thoracic spine"	0.02	0.03	0.00	0.05	0.2
7.					
8. "Pyelography"	2.33	0.67	0.49	3.49	15.0
9. "Bladder"	0.08	0.02	0.08	0.18	0.8
10. Pelvimetry	0.65	—	3.47	4.06	17.5
11. Salpingography	0.24	—	—	0.24	1.0
12.					
13. "Abdomen with obstetric"	0.88	0.24	2.73	3.85	16.6
14. "Barium enema"	0.01	0.04	0.00	0.05	0.2
15. "Barium swallow and meal"	0.02	0.08	0.00	0.10	0.4
16. Cholecystography	0.00	0.00	0.00	0.00	0.0
17. Chest	0.01	0.07	0.00	0.08	0.3
18. "Ribs and sternum – shoulder"	0.00	0.00	0.00	0.00	0.0
19. Arm	0.00	0.07	0.00	0.07	0.3
20. Lower leg	0.01	0.08	0.00	0.09	0.4
21. "Head + cervical spine"	0.01	0.02	0.00	0.03	0.1
22. Dental	0.00	0.01	0.00	0.01	0.0
23. Mass surveys	0.01	0.01	0.00	0.02	0.1
24. Others	0.01	0.44	0.00	0.45	1.9
TOTAL	8.0	8.1	7.1	23.2	100

APPENDIX V

FRANCE

The primary material

1. The estimate presented here is based upon data submitted by Reboul and Istin.[6] The authors assume the annual number of *radiographic* examinations in France to be 5,000,000 plus 1,300,000 examinations of employees and militaries. The distribution on various types of examinations is studied on 18.889 cases. The data are assumed to be representative for 1957.

2. The authors point out that the foetal exposure due to pelvimetry and obstetrical examinations is lower in France than in other countries, due to the low frequency of these examinations.

3. 28,000,000 *fluoroscopies* are performed annually, 19,000,000 of which are examinations of patients under age 30, mostly in mass chest examinations. There are only 2,000,000 *photofluoroscopies* per year. The gonad dose from photofluoroscopy has been estimated by Turpin, Dupire, Jammet and Lejeune.[60]

4. The authors consider their values to be minimum estimates.

Presentation of the material for this report

5. The French data include values of N_j for the whole material, and the corresponding values of d_j in most cases. Where the dose is not reported, an average dose, likely to be representative, has been used. These values are indicated with an asterisk in the table.

6. Values for the relative child expectancy (w_j/w) cannot be derived from the French data. However, an approximate figure can be calculated from the information on the fraction of patients under age 30, for each type of examination. The approximate figures differ little from the values of w_j/w presented in the table for England and Wales. Therefore, the British values may be regarded as fairly representative also for the French material, and they have accordingly been used in the calculations.

7. The contribution from radiography, 27 mrem, is most likely a very low estimate. An interesting feature of the French material is the remarkably high contribution of *fluoroscopy used in mass survey examinations.* Because of the uncertainty with regard to average viewing time and other factors determining the dose per examination, the total value 57 mrem must be considered uncertain by at least a factor of two.

DATA FOR EVALUATION OF THE GENETICALLY SIGNIFICANT DOSE FROM DIAGNOSTIC X-RAY EXPOSURE

A. ANNUAL CONTRIBUTION FROM 5,000,000 RADIOGRAPHIC EXAMINATIONS

(foetal exposure excluded)

APPENDIX V. TABLE I. FRANCE

No.	Examinations involving radiography	Females				Males				Total	
		1000 N_i/N	d_i mrem	w_i/w	$D_i^{(F)}$ mrem	1000 N_i/N	d_i mrem	w_i/w	$D_i^{(M)}$ mrem	D_i mrem	Per cent
1.											
2.	"Membres inf. 1/3 sup."	1.59	150	0.7	0.17	2.18	1,200	1.1	2.88	3.05	11.3
3.	"Bassin" (items 10 and 12 excluded)	3.30	1,200	0.9	3.56	3.13	1,500	0.6	2.82	6.38	23.7
4.	"Colonnes lombaires"	2.43	750	0.6	1.09	2.79	130	0.8	0.29	1.38	5.1
5.											
6.	"Colonnes dorsales"	1.70	20	0.7	0.02	2.13	6	0.8	0.01	0.03	0.1
7.	"Urographies"	1.38	2,100	0.5	1.45	1.54	380	0.4	0.23	1.68	6.2
8.	"Urètho-Cysto" (not incl. item 11)	0.25	1,200	0.5	0.15	0.30	2,000	0.4	0.24	0.39	1.4
9.											
10.	"Pelvimetries"	0.038	1,200*	0.9	0.04	—	—	—	—	0.04	0.1
11.	"Hysterographies"	0.46	1,700*	1.1	0.86	—	—	—	—	0.86	3.2
12.	"Grossesses"	0.26	1,600*	1.8	0.75	—	—	—	—	0.75	2.8
13.	"Pneumo et retropneumoperitoines"	0.043	300	0.6	0.01	0.074	160	0.6	0.01	0.02	0.1
	"Splenoportographies"	0.046	70		0.00	0.111	32		0.00	0.00	0.0
14.	"Grèle"	0.28	250*	0.2	0.01	0.21	75*	0.4	0.01	0.02	0.1
	"Lavement"	2.28	220		0.10	1.65	140		0.09	0.19	0.7
15.	"Oesophages"	0.51	6*	0.4	0.00	0.87	6*	0.4	0.00	0.00	0.0
	"Estomacs"	3.17	190		0.24	4.95	60		0.12	0.36	1.3
16.	"Vesicules"	1.97	40	0.2	0.02	1.20	28	0.3	0.10	0.12	0.4
17.	"Poumons"	20.7	9	1.3	0.24	28.9	13	1.3	0.49	0.73	2.7
	"Lipiodols"	0.042	250*	0.5	0.01	0.13	320	0.8	0.03	0.04	0.1
	"Arteriographie"	0.12	250*	0.5	0.02	0.24	320*	0.8	0.06	0.08	0.3
	"Tomographies"	1.07	1,900	0.5	1.02	2.93	1,500	0.8	3.52	4.54	16.9
18.	"Membres sup. 1/2 sup."	1.50	0.9*	0.7	0.00	1.85	0.4*	0.9	0.00	0.00	0.0
19/20.	"Membres sup./inf. 1/2 inf."	1.93	0.4*	1.1	0.00	3.74	0.4*	1.5	0.00	0.00	0.0
	"Extrémites osseuses"	2.41	0.3*	1.0	0.00	3.79	0.3*	1.2	0.00	0.00	0.0
21.	"Crânes"	2.57	4	1.5	0.02	4.37	4	1.6	0.03	0.05	0.2
	"Col. cervicales"	0.94	15	0.5	0.01	0.95	15	1.1	0.02	0.03	0.1
22.	—				0.00				0.00	0.00	0.0
23.	"Radiophotographies"	240	0.3	1.3	0.09	240	0.3	0.9	0.06	0.15	0.6
	TOTALS				10.32				10.74	20.9	77.4

B. ADDITIONAL CONTRIBUTION FROM 1,300,000 RADIOGRAPHIC EXAMINATIONS OF EMPLOYEES AND MILITARIES

Contribution estimated in proportion to number of examinations, photofluoroscopy excluded	5.2	19.3

C. ALLOWANCE FOR FOETAL EXPOSURE

Estimate from British values in proportion to the frequency of examinations

		U.K.: D_i (mrem)	U.K.: 1000 N_i/N	France: 1000 N_i/N		
10.	"Pelvimetries"	3.47	0.58	0.038	0.2	0.7
12.	"Grossesses"	2.73	1.94	0.26	0.4	1.5
				TOTAL RADIOGRAPHY:	27	100

D. CONTRIBUTION FROM FLUOROSCOPY

19,000,000 examinations under age 30, with an average gonad dose of 30 mrem per exam. (mostly mass surveys)

		1000 N_i/N	d_i (mrem)	w_i/w	
23.	"Examens systématiques"	452	30	2.21	30
				TOTAL DIAGNOSTIC:	57

APPENDIX VI

JAPAN

The data submitted by Japan[7] do not permit a presentation according to Equation (8). The following information is given:

Type of examination	*1000 N_j/N*	*d_j (mrem)*
(A) *Radiography:*		
Chest, large film	109	0.06–0.5
Chest, tomography	57	1–3
Abdomen	68	100
Mass surveys	260	0.05–0.4
Others	46	1
(B) *Fluoroscopy:*		
Chest	18	1.6–12.7
Abdomen	22	200–1000

From the above data, the *per capita* gonad dose from diagnostic X-ray exposure is estimated to be 10 - 30 mrem per year.

APPENDIX VII

NEW ZEALAND

1. No exposure data have been submitted from New Zealand, but it has been reported that an extensive survey of diagnostic exposure has been initiated. New Zealand has full records of all diagnostic X-ray plants in the country and a system of medical services that permits a quantitative assessment of virtually all diagnostic X-ray work done.

2. Data on the number of examinations have been reported[45] to the Committee and are presented in table I in the main text of annex C. A characteristic feature is the high annual number of dental examinations (0.24 *per capita*). 95 per cent of these are made on school children between the ages of 12 and 16.

3. The frequency of mass miniature chest examination (with an annual number of 0.09 *per capita*) is reported together with the information that 23 per cent of all notified cases of pulmonary tuberculosis are discovered by mass X-ray surveys, with a case yield of about 1.8 per 1,000 examinations.

APPENDIX VIII

NORWAY

The data submitted by Norway[8] do not permit any estimate of the genetically significant dose. Gonad doses have been measured by Koren and Maudal;[65] their annual consumption of X-ray films is 1.1 *per capita*, the values are included in the tables in appendix XI. As the contribution from diagnostic X-ray procedures to the genetically significant dose is likely to be high enough to warrant more detailed analysis, which is reported to be planned.

APPENDIX IX

SWEDEN

The primary material

1. The estimate of the genetically significant dose from diagnostic X-ray procedures in Sweden is based upon a report by Larsson.[9] The data are representative for 1955.

2. Dose measurements were performed on 1,957 patients in 17 X-ray departments. Of the patients, 394 were children. The age-distribution in the various types of examinations is based upon a material of 39,315 examinations.

3. The total number of examinations for 1955 was found to be 1,910,000. The annual increase during the period 1945-1954 was 15.5 per cent. The number of mass miniature radiographs during 1955 was estimated at 1,000,000.

4. In addition to the actually occurring doses, the author presents "possible" values found after simple measures to reduce the gonad exposure. If the indications for pelvimetry and obstetric examinations are made more restrictive, the achievable annual genetically significant dose that would result is estimated to be 15 mrem instead of the value of 38 mrem found for 1955.

Presentation of the material for this report

5. In the original paper the genetically significant dose was calculated for each sex as an average dose per productive gamete. The sum of these doses was taken to express the radiation burden to the zygote. The figures in the following table have been recalculated by the author to conform with the presentation in this report.

APPENDIX X

UNITED STATES OF AMERICA

The primary material

1. The estimate of the genetically significant dose for the United States of America is based upon a survey of literature up to about the middle of 1956, reported by Laughlin and Pullman[10]. In the report, which is only preliminary, the authors have computed the *probable* annual gonad dose per person up to age 30 years. They also give a *minimum* estimate.

2. The most characteristic feature of these data is that the surveyors have listed radiography and fluoroscopy separately and, in the case of fluoroscopy, also separated radiologists' examinations from those of non-radiologists.

3. The primary material of the Laughlin-Pullman report is shown in the tables I to VI, with regard to the estimate of the *probable* dose. The probable *per capita* gonad dose up to age 30 is found to be about 140 ± 100 mrem. The minimum estimate is 50 ± 30 mrem.

Presentation of the material for this report

4. As nothing is known about the actual child-expectancy of patients undergoing X-ray examinations, the first approximation has been to assume that it is not influenced by the nature of the condition for which the patient was examined. The value of w_j/w for each examination class would then depend only upon the age-distribution within the class. With this assumption, the annual gonad dose per person up to age 30 years may be taken as an approximate figure for the annual genetically significant dose. w_j/w has been calculated from the known values of N_j/N, d_j and this approximation of D_j. It has been necessary to assume that the dose per examination is the same for the two age-groups "12-29 years" and "over 12". Tables VII to XVI give the final presentation of the material.

Data for evaluation of the genetically significant dose from diagnostic X-ray exposure

Appendix IX. Table I. — **Sweden**

No.	Type of examination	Female adults: 1,000 N_j^*/N	Female adults: w_j^*/w	Female adults: d_j^* (mrem)	Female adults: D_j^* (mrem)	Female children: 1,000 N_j^*/N	Female children: w_j^*/w	Female children: d_j^* (mrem)	Female children: D_j^* (mrem)	Male adults: 1,000 N_j^*/N	Male adults: w_j^*/w	Male adults: d_j^* (mrem)	Male adults: D_j^* (mrem)	Male children: 1,000 N_j^*/N	Male children: w_j^*/w	Male children: d_j^* (mrem)	Male children: D_j^* (mrem)	Foetus: 1,000 N_j^*/N	Foetus: w_j^*/w	Foetus: d_j^* (mrem)	Foetus: D_j^* (mrem)	Subtotal (mrem): $D_j^{(F)}$ (mrem)	Subtotal (mrem): $D_j^{(M)}$ (mrem)	Subtotal (mrem): $D_j^{(Fet)}$ (mrem)	Total: D_j (mrem)	Total: Per cent
1.	"Hip"	4.3	0.10	260	0.11	0.12	2.47	400	0.14	2.5	0.08	1000	1.85	0.091	2.35	1600	0.34	[c]	2.41	260	0.01	0.25	2.19	0.01	2.45	6.5
2.	"Femur"	0.84	0.71	35	0.021	0.040	"	6.1	0.0006	1.7	0.89	830	1.25	0.066	"	960	0.15	[c]	"	35	0.006	0.022	1.40	0.006	1.43	3.8
3.	Pelvic region	3.8	0.25	200	0.19	0.30	"	280	0.21	3.6	0.41	870	1.29	0.45	"	1330	1.41	[c]	"	200	0.03	0.40	2.70	0.03	3.13	8.3
4., 5.	"Lumbar and sacral spine"	6.8	0.31	490	1.05	0.22	"	580	0.31	8.7	0.49	940	4.00	0.43	"	2270	2.30	[c]	"	490	0.14	1.36	6.30	0.14	7.80	20.6
6.	"Thoracic spine"	2.6	0.28	6.2	0.0046	0.026	"			3.2	0.03	3.3	0.01	<0.0082	"			[c]	"	6.2	<0.001	0.0046	0.01	<0.001	0.015	<0.1
7., 8.	"Intravenous urography"	3.6	0.42	925	1.40	0.22	"	445 (910)[d]	0.37	5.2	0.45	1240	2.91	0.10	"	930 (3880)[d]	0.57	[c]	"	925	0.16	1.77	3.48	0.16	5.41	14.3
9.	Urethrocystography	0.20	0.28	1940	0.11	0.011	"	1240	0.034	0.93	0.30	3700	1.05	0.035	"	6370	0.52	[c]	"	1940	0.016	0.14	1.57	0.016	1.73	4.6
10.	Pelvimetry	0.59	0.44[a]	1080	0.28	<0.0006	"			—	—	—	—	—	—	—	—	0.59	"	4500	6.4	0.28	—	6.4	6.68	17.6
11.	Hysterosalpingography	1.2	0.36[b]	2600	1.12	0.0036	"			—	—	—	—	—	—	—	—	—	—	—	—	1.12	—	—	1.12	3.0
12.	Obstetrical abdomen	0.59	0.44[a]	265	0.064	<0.0006	"			—	—	—	—	—	—	—	—	0.59	2.41	910	1.2	0.064	—	1.2	1.26	3.3
13.	"Abdomen survey"	2.4	0.30	1150	0.84	0.030	"		0.085	2.5	0.49	1360	1.65	0.040	2.35		0.13	[c]	"	1150	0.11	0.93	1.78	0.11	2.82	7.4
14.	"Colon"	4.8	0.20	1520	1.43	0.16	"		0.60	3.9	0.27	310	0.32	0.17	"	600	0.24	[c]	"	1520	0.21	2.03	0.56	0.21	2.80	7.4
15.	"Stomach"	17.1	0.27	29	0.13	0.17	"	105	0.044	12.8	0.48	14	0.086	0.065	"	75	0.011	[c]	"	29	0.02	0.17	0.097	0.02	0.29	0.8
16.	Cholecystography	8.5	0.35	16.8	0.050	0.017	"		0.0007	3.5	0.50	6.3	0.011	<0.0035	"		<0.0001	[c]	"	16.8	0.007	0.051	0.011	0.007	0.07	0.2
17., 18.	"Chest"	41.6	0.37	4.1	0.063	2.2	"	2.4	0.013	33.8	0.61	1.8	0.037	1.8	"	1.0	0.0042	[c]	"	4.1	0.005	0.076	0.041	0.005	0.12	0.3
19., 20., 21.	"Lower leg, skull, fore and upper arm, hand, foot"	39.6	0.41	0.5	0.008	4.4	"	<0.5	<0.0054	52.8	0.53	1	0.028	5.9	"	<1	<0.014	[c]	"	0.5	0.0015	<0.013	<0.042	0.0015	0.06	0.2
22.	Dental	128	0.41	≪1	≪0.052	27	"	≪1	≪0.067	124	0.53	<1	<0.066	28	"	<1	<0.066	[c]	"	≪1	≪0.10	≪0.12	<0.13	≪0.10	0.35	0.9
23.	Mass miniature (photofluoroscopy)	58.2	0.44	1.8	0.046	12.1	"	3.6	0.11	56.1	0.59	0.76	0.025	12.6	"	1.6	0.046	[c]	"	1.8	0.093	0.16	0.071	0.093	0.32	0.8
	Totals				7.0				2.0				14.6				5.8				8.5	9.0	20.4	8.5	37.9	100

[a] A correction of the normal age-specific child-expectancy has been made here.
[b] Every three women are expected to have a child subsequently.
[c] In all cases of foetal exposure except pelvimetry and obstetrical abdomen, the foetal contribution has been derived from the assumption that 5.6 per cent of the women in fertile ages were pregnant.
[d] Including two radiographs over the trigone.

Number of female examinations under age 30 per 1000 of total population
($1000n_j^{(F)}/N$)

Appendix X. Table I. USA

Exam. No.		Radiography: Radiologists and non-radiologists 0–11	Radiography: Radiologists and non-radiologists 12–29	Fluoroscopy: Radiologists 0–11	Fluoroscopy: Radiologists 12–29	Fluoroscopy: Non-radiologists 0–11	Fluoroscopy: Non-radiologists 12–29
1.	"Skeleton—pelvic region"	2.54[a]	2.81[c]			0.35[h]	0.50[i]
2.							
3.							
4.							
5.		0.40[b]					
6.							
7.	"Pyelography"		1.11	0.043[f]	0.90[f]	0.30[f]	0.28[f]
8.							
9.	"Urinary tract"		0.71				
10.	Pelvimetry	—	2.26				
11.	Salpingography	—	0.08				
12.	Abdomen (obstetrical)	—	0.62				
13.	"Abdomen and colon"	(1.0)	3.26	0.86	1.80	0.38	0.48
14.							
15.	Stomach and upper G.I.	(1.0)	3.53	1.04	2.16	0.25	0.60
16.	"Gall bladder"		0.81				
17.	Chest (lungs, heart, oesophagus)	(3.6)	9.5	0.22[g]	0.45[g]	(0.60)	1.44
18.							
19.	"Skeleton—extremities and chest"	(2.8)	3.26			(0.20)	0.48
20.							
21.	Head	(2.0)	2.17			(0.13)	0.24
22.	Dental	35[d,e]	275[d]				
23.	Mass surveys	(all ages (0–29):	20.4				

[a] Pelvis and hips.
[b] Lumbar spine.
[c] Including 0.09 from chiropractors.
[d] Each film counted as one examination.
[e] Children under 10 years.
[f] Genito-urinary region.
[g] Heart.
[h] Including 1/3 of all examinations of age-group under 2 years.
[i] Including 0.10 from chiropractors.

(Figures in brackets have been derived by an arbitrary split of a figure for a larger group of examination-classes.)

Female gonad dose per examination
($d_j^{(F)}$ in mrem)

Appendix X. Table II. USA

Exam. No.		Radiography: Radiologists and non-radiologists 0–11	Radiography: Radiologists and non-radiologists 12–29	Fluoroscopy: Radiologists 0–11	Fluoroscopy: Radiologists 12–29	Fluoroscopy: Non-radiologists 0–11	Fluoroscopy: Non-radiologists 12–29
1.	"Skeleton—pelvic region"	500[a]	1,000[b]			1,000[a]	3,000[b]
2.							
3.							
4.							
5.		1,300[a]					
6.							
7.	"Pyelography"		1,200	1,000[a]	3,000[a]	1,000[a]	3,000[a]
8.							
9.	"Urinary tract"		1,000				
10.	Pelvimetry	—	2,500				
11.	Salpingography	—	10,000				
12.	Abdomen (obstetrical)	—	260				
13.	"Abdomen and colon"	(550)	500	1,500	1,500	1,000	1,500
14.							
15.	Stomach and upper G.I.	(350)	300	750	750	500	350
16.	"Gall bladder"		200				
17.	Chest (lungs, heart, oesophagus)	(60)	0.3	15[a]	15[a]	(30)	10
18.							
19.	"Skeleton—extremities and chest"	(60)	0.5			(30)	5
20.							
21.	Head	(60)	0.2			(30)	5
22.	Dental	4[a]	2[a]				
23.	Mass surveys	(all ages 0–29):	3				

[a] See footnotes to table I.
[b] The dose from chiropractors has been assumed to be 1000 mrem/exam.

Annual female gonad dose per person under age 30

$$(1.98 \times \frac{n^{(F)}}{N} \times d_j^{(F)} \text{ in mrem})$$

Appendix X. Table III. USA

Exam. No.		Radiography: Radiologists and non-radiologists 0–11	Radiography: Radiologists and non-radiologists 12–29	Fluoroscopy: Radiologists 0–11	Fluoroscopy: Radiologists 12–29	Fluoroscopy: Non-radiologists 0–11	Fluoroscopy: Non-radiologists 12–29
1.							
2.		2.5[a]					
3.							
4.	"Skeleton—pelvic region"		5.6[b]			0.7[a]	2.6[b]
5.		1.0					
6.							
7.							
8.	"Pyelography"		2.6	0.1[a]	0.5[a]	0.6[a]	1.7[a]
9.	"Urinary tract"		1.4				
10.	Pelvimetry	—	11.2				
11.	Salpingography	—	1.6				
12.	Abdomen (obstetrical)	—	0.3				
13.							
14.	"Abdomen and colon"	(1.1)	3.2	2.6	5.3	0.8	1.4
15.	Stomach and upper G.I.	(0.7)	2.1	1.5	3.2	0.2	0.4
16.	"Gall bladder"		0.3				
17.	Chest (lungs, heart, oesophagus)	(0.4)	0.01	0.01[a]	0.01[a]	(0.04)	0.03
18.							
19.	"Skeleton—extremities and chest"	(0.03)	0.00			(0.01)	0.00
20.							
21.	Head	(0.02)	0.00			(0.01)	0.00
22.	Dental	0.3[a]	1.1[a]				
23.	Mass surveys	(all ages 0–29):	0.1				
	Total	6.5	29.5	4	9	2.5	6

[a] See footnotes to table I.

[b] Including 0.2 from chiropractors.

Number of male examinations under age 30, per 1,000 of total population

$$(1{,}000\ n_j^M/N)$$

Appendix X. Table IV USA

Exam. No.		Radiography: Radiologists and non-radiologists 0–11	Radiography: Radiologists and non-radiologists 12–29	Fluoroscopy: Radiologists 0–11	Fluoroscopy: Radiologists 12–29	Fluoroscopy: Non-radiologists 0–11	Fluoroscopy: Non-radiologists 12–29
1.							
2.		2.85[a]					
3.							
4.	"Skeleton—pelvic region"		3.11[c]			0.40[b]	0.55[i]
5.		0.45[b]					
6.							
7.							
8.	"Pyelography"		1.24	0.05[f]	0.10[f]	0.34[f]	0.31[f]
9.	"Urinary tract"		0.79				
10.	Pelvimetry	—	—				
11.	Salpingography	—	—				
12.	Abdomen (obstetrical)	—	—				
13.							
14.	"Abdomen and colon"	(1.1)	3.63	0.99	2.02	0.44	0.53
15.	Stomach and upper G.I.	(1.1)	3.93	1.19	2.43	0.29	0.67
16.	"Gall bladder"		0.91				
17.	Chest (lungs, heart, oesophagus)	(4.1)	10.6	0.25[g]	0.51[g]	(0.69)	1.60
18.							
19.	"Skeleton—extremities and chest"	(3.2)	3.63			(0.23)	0.53
20.							
21.	Head	(2.2)	2.42			(0.15)	0.36
22.	Dental	33[d,e]	172[d]				
23.	Mass surveys	(all ages 0–29):	16.7				

[a] Pelvis and hips.
[b] Lumbar spine.
[c] Including 0.09 from chiropractors.
[d] Each film counted as one exam.
[e] Children under 10 years.
[f] Genito-urinary region.
[g] Heart.
[h] Including 1/3 of all exams. of age-group under 2 years.
[i] Including 0.11 from chiropractors.

(Figures in brackets have been derived by an arbitrary split of a figure for a larger group of examination classes.)

MALE GONAD DOSE PER EXAMINATION
(d_j in mrem)

APPENDIX X. TABLE V — USA

Exam. No.		Radiography: Radiologists and non-radiologists 0–11	Radiography: Radiologists and non-radiologists 12–29	Fluoroscopy: Radiologists 0–11	Fluoroscopy: Radiologists 12–29	Fluoroscopy: Non-radiologists 0–11	Fluoroscopy: Non-radiologists 12–29
1.							
2.		1,100[a]					
3.	"Skeleton—pelvic region"		2,000[b]			2,000[a]	6,000[a]
4.							
5.		2,000[a]					
6.							
7.							
8.	"Pyelography"		2,000	2,000[a]	6,000[a]	2,000[a]	6,000[a]
9.	"Urinary tract"		300				
10.	Pelvimetry	—	—				
11.	Salpingography	—	—				
12.	Abdomen (obstetrical)	—	—				
13.							
14.	"Abdomen and colon"	(750)	200	750	750	2,000	750
15.	Stomach and upper G.I.	(750)	200	500	500	600	500
16.	"Gall bladder"		10				
17.	Chest (lungs, heart, oesophagus)	(120)	1.2	20[a]	20[a]	(40)	10
18.							
19.	"Skeleton—extremities and chest"	(120)	1.0			(40)	5
20.							
21.	Head	(120)	0.6			(40)	5
22.	Dental	12[a]	8[a]				
23.	Mass surveys	(all ages 0–29):	1				

[a] See footnotes to table I.

[b] The dose from chiropractors has been assumed to be 2,000 mrem/exam.

ANNUAL MALE GONAD DOSE PER PERSON UNDER AGE 30
$$(1.98 \times \frac{n_j^{(M)}}{N} \times d_j^M \text{ in mrem})$$

APPENDIX X. TABLE VI. — USA

Exam. No.		Radiography: Radiologists and non-radiologists 0–11	Radiography: Radiologists and non-radiologists 12–29	Fluoroscopy: Radiologists 0–11	Fluoroscopy: Radiologists 12–29	Fluoroscopy: Non-radiologists 0–11	Fluoroscopy: Non-radiologists 12–29
1.							
2.		6.2[a]					
3.	"Skeleton—pelvic region"		12[b]			1.6[a]	5.7[b]
4.							
5.		1.8					
6.							
7.							
8.	"Pyelography"		4.9	0.2[a]	1.2[a]	1.3[a]	3.7[b]
9.	"Urinary tract"		0.5				
10.	Pelvimetry	—	—				
11.	Salpingography	—	—				
12.	Abdomen (obstetrical)	—	—				
13.							
14.	"Abdomen and colon"	(1.6)	1.4	1.5	3.0	1.7	0.8
15.	Stomach and upper G.I.	(1.6)	1.6	1.2	2.4	0.3	0.7
16.	"Gall bladder"		0.02				
17.	Chest (lungs, heart, oesophagus)	(1.0)	0.03	0.01[a]	0.02[a]	(0.05)	0.03
18.							
19.	"Skeleton—extremities and chest"	(0.8)	0.01			(0.02)	0.00
20.							
21.	Head	(0.5)	0.003			(0.01)	0.00
22.	Dental	0.8[a]	2.7[a]				
23.	Mass surveys	(all ages 0–29):	0.03				
	TOTAL	14.5	23	3	6.5	5	11

[a] See footnotes to table I.

[b] Including 0.4 from chiropractors.

Number of female examinations per 1000 of total population
($1{,}000.N_j^{(F)}/N$)

Appendix X. Table VII. USA

Exam. No.		Radiography		Fluoroscopy			
		Radiologists and non-radiologists		Radiologists		Non-radiologists	
		0–11	Over 12	0–11	Over 12	0–11	Over 12
1. 2. 3. 4. 5. 6.	"Skeleton—pelvic region"	2.54 / 0.40	9.7			0.35	1.69
7. 8.	"Pyelography"		4.6	0.043	0.28	0.30	1.13
9.	"Urinary tract"		2.9				
10.	Pelvimetry	—	2.26				
11.	Salpingography	—	0.16				
12.	Abdomen (obstetrical)	—	0.75				
13. 14.	"Abdomen and colon"	(1.0)	12.4	0.86	6.1	0.38	2.47
15.	Stomach and upper G.I.	(1.0)	13.1	1.04	7.3	0.25	2.80
16.	"Gall bladder"		2.9				
17.	Chest (lungs, heart, oesophagus)	(3.6)	35.9	0.22	1.5	(0.60)	6.8
18. 19. 20.	"Skeleton—extremities and chest"	(2.8)	6.3			(0.20)	1.83
21.	Head	(2.0)	9.1			(0.13)	1.50
22.	Dental	35	515				
23.	Mass surveys	(All ages)	61				

Female gonad dose per examination
($d_j^{(F)}$ in mrem)

Appendix X. Table VIII. USA

Exam. No.		Radiography		Fluoroscopy			
		Radiologists and non-radiologists		Radiologists		Non-radiologists	
		0–11	Over 12[a]	0–11	Over 12[a]	0–11	Over 12[a]
1. 2. 3. 4. 5. 6.	"Skeleton—pelvic region"	500 / 1,300	1,000			1,000	2,600[b]
7. 8.	"Pyelography"	—	1,200	1,000	3,000	1,000	3,000
9.	"Urinary tract"	—	1,000				
10.	Pelvimetry	—	2,500				
11.	Salpingography	—	10,000				
12.	Abdomen (obstetrical)	—	260				
13. 14.	"Abdomen and colon"	(550)	500	1,500	1,500	1,000	1,500
15.	Stomach and upper G. I.	(350)	300	750	750	500	350
16.	"Gall bladder"		200				
17.	Chest (lungs, heart, oesophagus)	(60)	0.3	15	15	(30)	10
18. 19. 20.	"Skeleton—extremities and chest"	(60)	0.5			(30)	5
21.	Head	(60)	0.2			(30)	5
22.	Dental	4	2				
23.	Mass surveys	(All ages)	3				

[a] It has been assumed that the dose in the age-group over 12 years is the same as in the age-group 12–29.

[b] Weighted average including chiropractors' contribution.

Relative female child expectancy
$(w_j^{(F)}/w)$[a]

Appendix X. Table IX. USA

Exam. No.		Radiography: Radiologists and non-radiologists 0–11	Radiography: Radiologists and non-radiologists Over 12	Fluoroscopy: Radiologists 0–11	Fluoroscopy: Radiologists Over 12	Fluoroscopy: Non-radiologists 0–11	Fluoroscopy: Non-radiologists Over 12
1.							
2.		1.98					
3.							
4.	"Skeleton—pelvic region"		0.58			1.98	0.59
5.		1.98					
6.							
7.							
8.	"Pyelography"		0.48	1.98	0.64	1.98	0.49
9.	"Urinary tract"		0.48				
10.	Pelvimetry	—	2.0				
11.	Salpingography	—	1.0				
12.	Abdomen (obstetrical)	—	1.69				
13.							
14.	"Abdomen and colon"	1.98	0.52	1.98	0.58	1.98	0.38
15.	Stomach and upper G. I.	1.98	0.53	1.98	0.59	1.98	0.43
16.	"Gall bladder"		0.55				
17.	Chest (lungs, heart, oesophagus)	1.98	0.6	1.98	0.6	1.98	0.5
18.							
19.	"Skeleton—extremities and chest"	1.98	0.6			1.98	0.5
20.							
21.	Head	1.98	0.6			1.98	0.5
22.	Dental	1.98	1.1				
23.	Mass surveys	(All ages):	0.7				

[a] Figures back-calculated from tables II, III and VII.

Female contribution to the annual genetically significant dose
$(D_j^{(F)}$ in mrem)[a]

Appendix X. Table X. USA

Exam. No.		Radiography: Radiologists and non-radiologists 0–11	Radiography: Radiologists and non-radiologists Over 12	Fluoroscopy: Radiologists 0–11	Fluoroscopy: Radiologists Over 12	Fluoroscopy: Non-radiologists 0–11	Fluoroscopy: Non-radiologists Over 12
1.							
2.		2.5					
3.							
4.	"Skeleton—pelvic region"		5.6			0.7	2.6
5.		1.0					
6.							
7.							
8.	"Pyelography"		2.6	0.1	0.5	0.6	1.7
9.	"Urinary tract"		1.4				
10.	Pelvimetry	—	11.2				
11.	Salpingography	—	1.6				
12.	Abdomen (obstetrical)	—	0.3				
13.							
14.	"Abdomen and colon"	(1.1)	3.2	2.6	5.3	0.8	1.4
15.	Stomach and upper G. I.	(0.7)	2.1	1.5	3.2	0.2	0.4
16.	"Gall bladder"		0.3				
17.	Chest (lungs, heart, oesophagus)	(0.4)	0.01	0.01	0.01	(0.04)	0.03
18.							
19.	"Skeleton—extremities and chest"	(0.3)	0.00			(0.01)	0.00
20.							
21.	Head	(0.2)	0.00			(0.01)	0.00
22.	Dental	0.3	1.1				
23.	Mass surveys	(All ages):	0.1				
	Total	6.5	29.5	4	9	2.5	6

[a] Figures identical with those in table III.

NUMBER OF MALE EXAMINATIONS PER 1000 OF TOTAL POPULATION
$(1{,}000.N_j^{(M)}/N)$

APPENDIX X. TABLE XI. USA

Exam. No.		Radiography		Fluoroscopy			
		Radiologists and non-radiologists		Radiologists		Non-radiologists	
		0–11	Over 12	0–11	Over 12	0–11	Over 12
1.							
2.							
3.	"Skeleton—pelvic region"	2.85					
4.			11.0			0.40	1.91
5.							
6.		0.45					
7.							
8.	"Pyelography"		5.2	0.05	0.32	0.34	1.27
9.	"Urinary tract"		3.2				
10.	Pelvimetry	—	—				
11.	Salpingography	—	—				
12.	Abdomen (obstetrical)	—	—				
13.							
14.	"Abdomen and colon"	(1.1)	13.9	0.99	6.9	0.44	2.79
15.	Stomach and upper G. I.	(1.1)	14.7	1.19	8.2	0.29	3.17
16.	"Gall bladder"		3.2				
17.	Chest (lungs, heart, oesophagus)	(4.1)	40.5	0.25	1.7	(0.69)	7.6
18.							
19.	"Skeleton—extremities and chest"	(3.2)	7.0			(0.23)	2.1
20.							
21.	Head	(2.2)	10.3			(0.15)	1.7
22.	Dental	33	580				
23.	Mass surveys	(All ages):	69				

MALE GONAD DOSE PER EXAMINATION
$(d_j^{(M)}$ in mrem)

APPENDIX X. TABLE XII. USA

Exam. No.		Radiography		Fluoroscopy			
		Radiologists and non-radiologists		Radiologists		Non-radiologists	
		0–11	Over 12[a]	0–11	Over 12[a]	0–11	Over 12[a]
1.							
2.							
3.	"Skeleton—pelvic region"	1,100					
4.			2,000			2,000	5,200[b]
5.							
6.		2,000					
7.							
8.	"Pyelography"		2,000	2,000	6,000	2,000	6,000
9.	"Urinary tract"		300				
10.	Pelvimetry	—	—				
11.	Salpingography	—	—				
12.	Abdomen (obstetrical)	—	—				
13.							
14.	"Abdomen and colon"	(750)	200	750	750	2,000	750
15.	Stomach and upper G. I.	(750)	200	500	500	600	500
16.	"Gall bladder"		10				
17.	Chest (lungs, heart, oesophagus)	(120)	1.2	20	20	(40)	10
18.							
19.	"Skeleton—extremities and chest"	(120)	1.0			(40)	5
20.							
21.	Head	(120)	0.6			(40)	5
22.	Dental	12	8				
23.	Mass surveys	(All ages):	1				

[a] It has been assumed that the dose in the age-group over 12 years is the same as in the age-group 12–29.

[b] Weighted average including chiropractors' contributions.

Relative male child expectancy
$(w_1^{(M)}/w)$[a]

Appendix X. Table XIII. USA

Exam. No.		Radiography		Fluoroscopy			
		Radiologists and non-radiologists		Radiologists		Non-radiologists	
		0–11	Over 12	0–11	Over 12	0–11	Over 12
1. 2. 3. 4. 5. 6.	"Skeleton—pelvic region"	1.98 1.98	0.55			1.98	0.57
7. 8.	"Pyelography"		0.47	1.98	0.62	1.98	0.48
9.	"Urinary tract"		0.5				
10.	Pelvimetry	—	—				
11.	Salpingography	—	—				
12.	Abdomen (obstetrical)	—	—				
13. 14.	"Abdomen and colon"	1.98	0.50	1.98	0.58	1.98	0.4
15.	Stomach and upper G. I.	1.98	0.54	1.98	0.59	1.98	0.4
16.	"Gall bladder"		0.6				
17.	Chest (lungs, heart, oesophagus)	1.98	0.6	1.98	0.6	1.98	0.4
18. 19. 20.	"Skeleton—extremities and chest"	1.98	1			1.98	0.4
21.	Head	1.98	0.6			1.98	0.4
22.	Dental	1.98	0.6				
23.	Mass surveys	(All ages)	0.7				

[a] Figures back-calculated from tables V, VI and XI.

Male contribution to the annual genetically significant dose
$(D_1^{(M)}$ in mrem)[a]

Appendix X. Table XIV. USA

Exam. No.		Radiography		Fluoroscopy			
		Radiologists and non-radiologists		Radiologists		Non-radiologists	
		0–11	Over 12	0–11	Over 12	0–11	Over 12
1. 2. 3. 4. 5. 6.	"Skeleton—pelvic region"	6.2 1.8	12			1.6	5.7
7. 8.	"Pyelography"		4.9	0.2	1.2	1.3	3.7
9.	"Urinary tract"		0.5				
10.	Pelvimetry	—	—				
11.	Salpingography	—	—				
12.	Abdomen (obstetrical)	—	—				
13. 14.	"Abdomen and colon"	(1.6)	1.4	1.5	3.0	1.7	0.8
15.	Stomach and upper G. I.	(1.6)	1.6	1.2	2.4	0.3	0.7
16.	"Gall bladder"		0.02				
17.	Chest (lungs, heart, oesophagus)	(1.0)	0.03	0.01	0.02	(0.05)	0.03
18. 19. 20.	"Skeleton—extremities and chest"	(0.8)	0.01			(0.02)	0.01
21.	Head	(0.5)	0.00			(0.01)	0.00
22.	Dental	0.8	2.7				
23.	Mass surveys	(All ages)	0.03				
	Total	14.5	23	3	6.5	5	11

[a] Figures identical with those in table VI.

APPENDIX X. TABLE XV. USA

Exam. No.		d_j mrem	$n_j/N = N_j/N$ x1,000	w_j/w (back-calculated)	D_j mrem[a]
1.	"Skeleton—pelvic region"				
2.					
3.					
4.					
5.					
6.					
7.	"Pyelography"				
8.					
9.	"Urinary tract"				
10.	Pelvimetry	4,000	2.53	1.98	20.0
11.	Salpingography				
12.	Abdomen (obstetrical)	400	0.88	1.98	0.7
13.	"Abdomen and colon"				
14.					
15.	Stomach and upper G.I.				
16.	"Gall bladder"				
17.	Chest (lungs, heart, oesophagus)	0.3	10.5	1.98	0.01
18.					
19.	"Skeleton—extremities and chest"				
20.					
21.	Head				
22.	Dental				
23.	Mass surveys				
24.	Others				
	TOTAL				20.7

[a] 1/0.67 of the figures given by Laughlin and Pullman.

GENETICALLY SIGNIFICANT DOSE (D_j IN MREM); SUMMARY TABLE

APPENDIX X. TABLE XVI. USA

Exam. No.		*Children*	*Female adults*	*Male adults*	*Foetal*	*Total*	*Per cent*
1.	"Skeleton—pelvic region"	13.8	8.2	17.7		39.7	28
2.							
3.							
4.							
5.							
6.							
7.	"Pyelography"	2.2	4.8	9.8		16.8	12
8.							
9.	"Urinary tract"		1.4	0.5		1.9	1.3
10.	Pelvimetry	—	11.2	—	20.0	31.2	22
11.	Salpingography	—	1.6	—		1.6	1.1
12.	Abdomen (obstetrical)	—	0.3	—		0.3	0.2
13.	"Abdomen and colon"	9.3	9.9	5.2	0.7	25.1	18
14.							
15.	Stomach and upper G.I.	5.5	5.7	4.7		15.9	11
16.	"Gall bladder"		0.3	0.0		0.3	0.2
17.	Chest (lungs, heart, oesophagus)	1.5	0.1	0.1	0.0	1.7	1.2
18.							
19.	"Skeleton—extremities and chest"	1.1	0.0	0.0		1.1	0.8
20.							
21.	Head	0.7	0.0	0.0		0.7	0.5
22.	Dental	1.1	1.1	2.7		4.9	3.5
23.	Mass surveys	[a]	0.1	0.0		0.1	0.1
	TOTAL	35.2	44.7	40.7	20.7	141	100

[a] Included in adult figures.

DATA ON DIAGNOSTIC X-RAY EXPOSURE: GONAD DOSE PER EXAMINATION FOR THE MOST IMPORTANT EXPOSURE CLASSES

APPENDIX XI

The tables I to XIV have been taken from the report of the ICRP/ICRU Joint Study Group. They show estimates of various authors of the gonad doses due to given types of examinations. The wide variations probably result from different techniques rather than from uncertainty in measurements. Hence the lower values indicate what levels may be achieved with good practice. Further details and references are given in the ICRP/ICRU Study Group report.

TABLE I. HIPS

Reference	*Technical data*	*Measurements made on*	*Remarks*	*Gonad dose per examination (mrad)*	
				Male	*Female*
Hammer-Jacobsen (1957) Denmark[4]	62–64 kv, 400–450 mAs FFD = 100 cm 2 films per examination	Patients: 12 male 9 female		567 (20–3600)	53 (30–100)
Larsson Sweden[9]	60–70 kv, 200–500 mAs 3 films per examination	Patients: 19 male 18 female		1150 (100–2600)	205 (75–450)
Laughlin and Pullman (1957) U.S.A.[10]			Years: 0– 2 2– 7 7–12 12–30	480 840 2100 650–2000	270 420 900 600–1000
Stanford and Vance (1955) U.S.A.[58]	68 kv, 200 mAs FFD = 90 cm	Patients		710	210

TABLE II. FEMUR

Reference	*Technical data*	*Measurements made on*	*Remarks*	*Gonad dose per examination (mrad)*	
				Male	*Female*
Hammer-Jacobsen (1957) Denmark[4]	58–60 kv, 250 mAs FFD = 100 cm 2 films per examination	Patients: 7 male 4 female		1393 (50–3500)	63 (20–100)
Koren and Maudal Norway[65]	62 kv, 250 mAs FFD = 100 cm 2 films per examination	Phantom		73	9·6
Larsson Sweden[9]	50–78 kv, 80 mAs	Patients: 6 male 2 female		65–650	50
Laughlin and Pullman (1957) U.S.A.[10]			Years: 12–30	1650	300

TABLE III. PELVIS

Reference	Technical data	Measurements made on	Remarks	Gonad dose per film (mrad)		Gonad dose per examination (mrad)	
				Male	Female	Male	Female
Hammer-Jacobsen (1957) Denmark[4]	60–63 kv, 200–360 mAs FFD = 100 cm 1–2 films per examination	Patients: 7 male 1 female				567 (50–2500)	70
Koren and Maudal Norway[65]	70 kv. 250 mAs FFD = 100 cm	Phantom		3580	96	3580	96
Larsson Sweden[9]	59–64 kv, 500 mAs FFD = 100 cm 1 film per examination	Patients: 16 male 20 female				1010 (50–2800)	190 (100–300)
Laughlin and Pullman (1957) U.S.A.[10]			Years: 0– 2 2– 7 7–12 12–30			480 840 2100 1650–2000	270 420 900 600–1000
Stanford and Vance (1955) U.K.[58]	65 kv, 100 mAs FFD = 90 cm	Patients	AP	1100	210	1100	210
Ardran and Crooks (1957) U.K.[25]	65 kv, 100 mAs FFD = 90 cm, no extra filter		Normal technique	2000			
	65 kv, 100 mAs FFD = 90 cm, 3mm Al-filter			670			
	75 kv, 80 mAs FFD = 110 cm, 3 mm Al-filter.		'AERE'† technique	480	80*		
	The same, but testes covered with lead			20			

* Measurement made on phantom.
† Atomic Energy Research Establishment.

TABLE IV. LUMBAR SPINE

Reference	*Technical data*	*Measurements made on*	*Remarks*	*Gonad dose per film (mrad)*		*Gonad dose per examination (mrad)*	
				Male	*Female*	*Male*	*Female*
Hammer-Jacobsen (1957) Denmark[4]	65–84 kv, 1250 mAs FFD = 100 cm 3 films per examination	Patients: 22 male 22 female				104 (10-400)	222 (20–600)
Koren and Maudal Norway[65]	68kv, 310 mAs FFD = 100 cm	Phantom	AP	4.5	60	4.5	60
	75 kv, 500 mAs FFD = 90 cm		Lat.	6	91	6	91
Larsson Sweden[9]	65–70 kv, 500 mAs FFD = 90–100 cm 4 films per examination	Patients: 12 male 7 female	Lumbar spine and lumbo-sacral region			375 (68–1180)	680 (490–860)
Laughlin and Pullman (1957) U.S.A.[10]			Years: 0– 2 2– 7 7–12			2700 2400 900	900 1050 2190
Stanford and Vance (1955) U.K.[58]	68 kv, 200 mAs FFD = 90 cm	Patients	AP	24	227	24	227
	72 kv, 500 mAs FFD = 90 cm		Lat.	26·6	86	26·6	86
	120 kv, 20 mAs FFD = 90 cm		AP	6	40	6	40
	120 kv, 60 mAs FFD = 90 cm		Lat.	7	16	7	16
Ardran and Crooks (1957) UK[25]	68 kv, 200 mAs FFD = 90 cm, no extra filter		Normal technique	24			
	68 kv, 200 mAs FFD = 90 cm, 3 mm Al-filter			6·0			
	75 kv, 80 mAs FFD = 110 cm 3 mm Al-filter		'AERE'† technique	1·0	95*		
	The same, but testes covered with lead			0·5			

* Measurement made on phantom.
† Atomic Energy Research Establishment.

TABLE V. INTRAVENOUS PYELOGRAPHY

Reference	Technical data	Measurements made on	Remarks	Gonad dose per film (mrad)		Gonad dose per examination (mrad)	
				Male	Female	Male	Female
Hammer-Jacobsen (1957) Denmark[4]	61–65 kv, 3300–4300 mAs FFD = 130–143 cm 6 films per examination	Patients: 50 male 50 female	Adults Adults			1383 (100–4000) †	424 (50–4000)
	65–73 kv, 650–1700 mAs FFD = 130–143 cm 6 films per examination	Patients: 14 male 8 female	Childen under 15 years			654 (100–1600)	706 (100–3800)
LeFebvre and Serra (1957) France	10 films 12 films 16 films	Patients	Children: 3 months 3 years 6 years	50 84 95	30 56 87	500 1008 1520	300 678 1384
Larsson Sweden[9]	66–120 kv, 95 mAs 12–26 films per examination	Patients: 25 male 17 female	Hospital 1			790 (141–2160)	1820 (935–2680)
	55 kv, 250–270 mAs 5–11 films per examination	Patients: 10 male	Hospital 2			1300 (22*–2500)	
Laughlin and Pullman (1957) U.S.A.[10]			12–30 years Pyelography			100–2000	200–1200
Stanford and Vance (1955) U.K.[58]	72 kv, 100 mAs FFD = 90 cm 6 films per examination	Patients				486	1290
Ardran and Crooks (1957) U.K.[25]	75 kv, 80 mAs FFD = 110 cm 3 mm Al added	Male: patients Female: phantom		0·5*	95		

* With lead rubber over the scrotum.
† Doses reduced to 1–3% by shielding of scrotum.

TABLE VI. RETROGRADE PYELOGRAPHY

Reference	Technical data	Measurements made on	Remarks	Gonad dose per examination (mrad)	
				Male	Female
Hammer-Jacobsen (1957) Denmark[4]	63–67 kv, 4000 mAs FFD = 130—143 cm 7 films per examination	Patients: 8 male 9 female		2580 (700–3800)	1136 (200–4000)
Laughlin and Pullman (1957) U.S.A.[10]			12–30 years Pyelography	100–2000	200–1200

TABLE VII. URETHROCYSTOGRAPHY

Reference	Technical data	Measurements made on	Remarks	Gonad dose per examination (mrad)	
				Male	Female
Hammer-Jacobsen (1957) Denmark[4]	71 kv, 3285 mAs FFD = 137 cm 6 films per examination	Patients: 7 male	Urethrography	4209 (2700–8400)	
	63–87 kv, 2000–2850 mAs FFD = 100–130 cm 5 films per examination	Patients: 2 male 2 female	Cystography	5261 (3500–7000)	460 (350–560)
	102–109 kv, 357–476 mAs FFD = 90 cm 9 films per examination	Patients: 9 male 9 female	Urethrocystography during micturition Adults	7841 (2400–17200)	669 (200–1500)
	79–86 kv, 256–341 mAs FFD = 90 cm 8 films per examination	Patients: 6 male 5 female	Under 15	2314 (200–4700)	205 (120–330)
Koren and Maudal Norway[65]	75 kv, 200 mAs 100 kv, 500 mAs FFD = 60 cm 1+4 films per examination	Phantom	AP Lat.		210 104 314
Larsson Sweden[9]	80–100 kv	Patients: 26 male 16 female	Hospital 1	4100 (1000–11000)	1000 (550–1650)
	100–200 mAs 5–15 films per examination	Patients: 5 male	Hospital 2	760 (320–1240)	
Laughlin and Pullman (1957) U.S.A.[10]	Radiography		Years: 12–30	100–300	200–1000
	Fluoroscopy		Years: 0–12 12–30	500–2000 500–6000	500–1000 500–3000

TABLE VIII. PELVIMETRY

Reference	*Technical data*	*Measurements made on*	*Remarks*	*Gonad dose per film (mrad)*	*Gonad dose per examination (mrad)*
				female	*female*
Hammer-Jacobsen (1957) Denmark[4]	81–85 kv, 1354 mAs FFD = 100 cm 2–3 films per examination	15 patients	AP+Lat.		738 (400–1400)
	84–92 kv, 1250 mAs FFD = 97 cm 3–4 films per examination	4 patients	Stereoscopic AP+Lat.		906 (650–1300)
Koren and Maudal Norway[65]	78 kv, 310 mAs FFD = 100 cm	Phantom	AP	86	86
	85 kv, 500 mAs FFD = 90 cm		Lat.	76	76
Larsson Sweden[9]	2 films: 90 kv 640 mAs 1 film: 90 kv 95 mAs FFD = 90–100 cm	12 patients	3 different projections		1500 (760–2500)
Laughlin and Pullman (1957) U.S.A.[10]					700–2500
Stanford and Vance (1955) U.K.[58]	120 kv, 100 mAs 120 kv, 50 mAs FFD = 90 cm	Patients	AP Lat.	240 840	

TABLE IX. SALPINGOGRAPHY

Reference	*Technical data*	*Measurements made on*	*Remarks*	*Gonad dose per examination (mrad)*
				Female
Hammer-Jacobsen (1957) Denmark[4]	69 kv, 1259 mAs FFD = 100 cm 2–7 films per examination	7 patients		197 (140–270)
Larsson Sweden[9]	65–90 kv, 120–150 mAs 6–11 films per examination	32 patients		2650 (1100–6700)
Laughlin and Pullman (1957) U.S.A.[10]				600–1000

TABLE X. ABDOMEN

Reference	Technical data	Measurements made on	Remarks	Gonad dose per examination (mrad)	
				Male	Female
Hammer-Jacobsen (1957) Denmark[4]	63–70 kv, 600 mAs FFD = 100–143 cm 1 film per examination	Patients: 5 male 4 female	AP	610 (40–1800)	85 (40–100)
	71 kv, 750 mAs FFD = 100 cm 1–2 films per examination	Patients: 21 female	Obstetric		90 (60–600)
Koren and Maudal Norway[65]	80 kv, 180 mAs FFD = 100 cm 3 films per examination	Phantom		7·8	120
Larsson Sweden[9]	Female 4–13 films per examination. Male 3–7 films per examination. Sometimes fluoroscopy, 1·5–2 min.	Patients: 7 male 7 female		450–2725	18–1280
Laughlin and Pullman 1957) U.S.A.[10]	Abdomen and colon radiography		Years: 0– 2 2– 7 7–12 12–30	450 930 750 10–200	240 390 720 460–500
Stanford and Vance (1955) U.K.[58]	72 kv, 100 mAs FFD = 90 cm	Patients	AP	69	200
	80 kv, 150 mAs FFD = 90 cm		Obstetric		200
Ardran and Crooks (1957) U.K.[25]	75 kv, 60 mAs FFD = 110 cm 3 mm Al-filter added	Male: patients Female: phantom	AP	0·5*	75

* With lead rubber protection.

TABLE XI. BARIUM ENEMA

Reference	Technical data	Measurements made on	Remarks	Gonad dose per examination (mrad)	
				Male	Female
LeFebvre and Serra (1957) France	15 films 7 films 9 films	Patients	Children: 3 months 3 years 6 years	450 700 900	400 455 800
Larsson Sweden[9]	About 10 films: mean fluoroscopy time 7 min.	Patients: 31 male 15 female		255 (52–485)	2065 (1075–2920)
Laughlin and Pullman (1957) U.S.A.[10]	Radiography		Abdomen & colon 12–30 years	140–200	420–500
	Fluoroscopy		Lower G.I.T. 12–30 years	0–750	420–1500
	Fluoroscopy		Lower G.I.T. Children	420–750	420–1500
Stanford and Vance (1955) U.K.[58]	Fluoroscopy: 70 kv, 2 mA 3 min.	Patients		40	20

TABLE XII. BARIUM SWALLOW AND MEAL

Reference	Technical data	Measurements made on	Remarks	Gonad dose per examination (mrad)	
				Male	Female
			Children:		
LeFebvre and Serra (1957) France	20 films		3 months	220	
	16 films	Patients	3 years	496	
	20 films		6 years	220	
Koren and Maudal Norway[65]	75 kv, 60mAs FFD = 60 cm 12 films per examination	Phantom		2·9	144
	Fluoroscopy: 70 kv, 3 mA, 3 min. FSD = 40 cm	Phantom		1·2	45
Larsson Sweden[9]	80–110 kv 40–80 mAs 10–15 films	Patients: 25 male 25 female	Hospital 1	12·5 (2·7–29)	33 (8·5–55)
	Mean fluoroscopy time 7 min.	Patients: 25 male 25 female	Hospital 2	4·3 (2·1–13·6)	31 (7·8–78)
Laughlin and Pullman (1957) U.S.A.[10]	Radiography		Stomach & upper G.I.T. 12–30 years	60–200	200–300
			Upper G.I.T. 12–30 years	0–500	200–750
	Fluoroscopy		Upper G.I.T. Children	200–500	200–750
Stanford and Vance (1955) U.K.[58]	Fluoroscopy 70 kv, 2 mA 3 min.	Patients		20	9
Ardran and Crooks (1957) U.K.[25]	Fluoroscopy with image intensifier 75 kv, 0·5 mA 5 min. 5 mm Al-filter added	Male: patients Female: phantom		5	5

TABLE XIII. CHOLECYSTOGRAPHY

Reference	Technical data	Measurements made on	Remarks	Gonad dose per examination (mrad)	
				Male	Female
Koren and Maudal Norway[65]	80 kv, 125 mAs FFD = 100 cm 5 films per examination	Phantom		6·7	260
Larsson Sweden[9]	60–80 kv 35–200 mAs 4–6 films per examination.	Patients: 26 male 25 female	Hospital 1	3·1 (1·3–6·5)	19 (10–41)
	Fluoroscopy 80 kv, 3 mA, 1·2–2·5 min.	Patients: 16 male	Hospital 2	7·1 (4·3–11)	
Laughlin and Pullman (1957) U.S.A.[10]	Radiography		12–30 years	0–10	75–200
Stanford and Vance (1955) U.K.[58]	70 kv, 150 mAs FFD = 90 cm 3 films per examination	Patients		1·8	15·6

TABLE XIV. CHEST

Reference	Technical data	Measurements made on	Remarks	Gonad dose per film (mrad)		Gonad dose per examination (mrad)	
				Male	Female	Male	Female
LeFebvre and Serra (1957) France		Patients	Children: 3 months	5			
Koren and Maudal Norway[65]	80 kv, 27 mAs FFD = 150 cm	Phantom	PA	<1	1·0	<1	1·0
	95 kv, 60 mAs FFD = 150 cm		Lat.	<1	1·5	<1	1·5
Larsson Sweden[9]	3–5 films per examination & fluoroscopy 70–80 kv, 2–2·5 mA 1–3 min	Patients: 78 male 22 female				1·6 (0·9–2·7)	4·6 (2·6–10·8)
Laughlin and Pullman (1957) U.S.A.[10]	Radiography		Years: 0– 2			0–450	0–240
			2–12			0–5	0–5
			12–30			0–1·2	0–0·3
	Fluoroscopy					0–40	0–30
Sanford and Vance (1955) U.K.[58]	68 kv	Patients	PA	0·36	0·07	0·36	0·07
Ardran and Crooks (1957) U.K.[25]	Radiography FFD = 180 cm 3 mm Al-filter added.	Male: patients Female: phantom	PA	0·01	0·02	0·01	0·02
	Fluoroscopy with image intensifier 75 kv, 0·5 mA 3 min., 5 mm Al-filter added	Male: patients Female: phantom				3·0	3·0

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Annex D

ENVIRONMENTAL CONTAMINATION

TABLE OF CONTENTS

I. Radioactive fall-out

1. In a nuclear explosion, several hundred radioactive isotopes are produced from fission. With exception of a small number of isotopes they have short half-lives and decay rapidly. In addition to fission products and residual fissionable material, a number of neutron-induced radioisotopes are produced. Their nature depend on the surrounding materials. Also, most of the radioisotopes formed by neutron-induction have short half-lives, usually less than a few hours.

2. The radioisotopes formed in a nuclear explosion are distributed by meteorological processes and eventually reach the surface of the earth. They enter the human body in several ways: first, by direct inhalation of airborne material; second, through uptake and deposition on vegetation eaten by humans; third, by transfer through animals and, fourth, by contamination of water supplies.

3. In addition to considering the exposure from material taken into the body, it is necessary to consider external radiation exposure. Except at the immediate site of the explosion, external radiation from airborne material is negligible in comparison with the external radiation from fission products deposited on the ground. The external radiation from deposited fission products depends mainly on their activity, half-lives and gamma emission characteristics.

4. Materials entering the human body deliver a dose which is closely related to the time they are retained by the body. This means that many of the isotopes produced in fission do not present radiation hazards since they do not enter significantly into metabolic processes. Attention has therefore been centred on isotopes which are potentially hazardous by reason of: (1) high fission yield, (2) fairly long physical half-life, (3) high absorption by the body and (4) long biological retention time. Special consideration is given to elements that concentrate in specific tissues, even though they do not have all the characteristics described. Using these criteria, the most important isotopes would be expected to be Sr^{90} and Cs^{137}.

5. In addition to the fission products and certain neutron-induced activities, some of the residual fissionable material, such as isotopes of uranium and plutonium, will also be distributed by meteorological processes and can be hazardous since they are alpha emitting bone seekers. However, the absorption by the body is very low and at present there is no evidence of any uptake of these materials in human tissues.

Fall-out mechanisms

6. The fireball from a nuclear explosion in the megaton* range cools so slowly that a major part of the fission products enter the stratosphere, where they become widely distributed. From this reservoir, the fission products fall onto the earth's surface over a period of many years (stratospheric fall-out). These fission products therefore consist mainly of long-lived isotopes. The mechanism of transfer from the stratosphere to the troposphere is not completely understood.

7. The heat of the fireball from explosions in the kiloton* range is dissipated quite rapidly and the fission products do not normally rise above the tropopause. The radioactive cloud from an explosion may travel many times around the earth and, during this time, the tropospheric fall-out is deposited at latitudes fairly close to that of the explosion. The relative magnitude of the contribution of the stratospheric and tropospheric components to the deposit therefore is different for different localities. Half the radioactive material in the troposphere is removed by deposition, mainly through rainfall, in about three weeks[1] and the deposition is effectively complete within three months. This deposit consists mainly of isotopes of fairly short half-life. At the present time the tropospheric fall-out is deposited intermittently during the year and a certain deposit of short-lived activities is built up and maintained. Isotopes of special concern for this report are Sr^{89}, Zr^{95}, Ru^{103}, Ru^{106}, Ba^{140} and Ce^{144}.

8. If the fireball touches or comes close to the ground in a nuclear explosion, there will be a local fall-out that constitutes a significant fraction of the total activity produced. This type of fall-out consists of radioactivity carried down by relatively large particles and in addition to fission products, contains shortlived isotopes produced by neutron induction in the material from the ground drawn into the fireball. This annex is concerned mainly with stratospheric and tropospheric fall-out.

Measurement of fall-out

9. Measurements have been undertaken to determine concentrations of radioactivity due to fall-out in air, soil and biological material, especially foodstuffs and human bone. Emphasis has been placed on a determination of the world-wide distribution of Sr^{90}. A survey of methods which have been found to be valuable in relation to the work of this Committee is given in annex E, and all relevant data from fall-out measurements that are submitted to this Committee are collected in tables XIV to XX and in the map at the end of the volume.

Airborne activity

10. Air samples can be obtained by filtration of air or by electrostatic precipitation. Studies of vertical distribution of fission products in the atmosphere have been made using filters carried by aircrafts or balloons. The samples are counted for total beta activity after decay of natural radioactivity or analysed for individual nuclides after radiochemical separation. One cause of uncertainty in the measurement of airborne activity at high altitude is in many cases the insufficient knowledge of the collection efficiency for this particulate activity.

11. Measurements at ground level in 1956-1957 show a concentration of Sr^{90} from 10^{-19} to 10^{-17} c/l of air[2-5]. For altitudes up to about 10,000 metres, the amount of fission products per kg of air increases slowly with altitude, but the rate of increase is much greater above the tropopause[2,6,7]. At the present time there are too few data available to permit a complete inventory of the stratospheric content.

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.

* In a nuclear explosion the total energy release is compared with the energy release by TNT (trinitrotoluene) when it explodes. Thus a 1 kiloton nuclear explosion is one which produces the same energy as the explosion of 1 kiloton (10^3 tons) of TNT, namely of about 10^{12} calories. A 1 megaton explosion similarly would correspond to the explosion of 1 megaton (10^6 tons) of TNT.

Fall-out deposit

12. Fall-out deposit measurements are necessary to estimate the external irradiation of man and the amount of specific isotopes likely to enter the biological food-chains and so eventually the body.

13. Many countries are measuring fall-out rate and accumulated deposit. At present, there are available to this Committee results from about 350 stations. However, large areas of the earth are not covered by the survey and not all the stations and laboratories operate at the same technical level. The results received by the Committee, however, allow a number of useful calculations to be made.

14. Soil analysis[D29] and various types of collectors, are used for studying fall-out deposit. Table I gives some technical information on these collectors. The agreement between results obtained by different methods of collection is reasonably good.

15. The location of sampling stations is of the utmost importance in obtaining representative samples. The location of new stations should be determined in consultation with meteorologists to assure a representative collection of precipitation (especially in areas where snow-fall is important).

16. With daily collection on gummed film or gauze, the amount of long-lived nuclides in the samples is generally very low; and, owing to the large soluble fraction, the washing effect of rainfall is considerable. For these reasons the radiochemical determination of Sr^{90} in these samples is valueless. The Sr^{90} content can, however, be computed by measuring the total beta activity of the samples and following its decay (assuming that all the activity originated in a single test).[8] However, in the present situation, with stratospheric mixture of materials from different tests, this computational method is unreliable unless it is repeatedly calibrated against radiochemical determinations on samples collected by the pot method.[9,10] A more refined method for the computation, taking into account the stratospheric reservoir, has recently been worked out, but this method is based on data that are not generally available.[10] The advantages of the gauze or gummed film is that they allow a daily survey of fall-out at many different stations.

17. Results reported to the Committee up to March 1958 are shown in tables XIV, XV and XVII and in the map at the end of the volume where the fall-out deposit at 1 July 1957 is plotted.

18. The world-wide fall-out rate and deposit of Sr^{90} is uneven and there are variations with latitude which show maxima in the region between 30° and 50° North and South, with a minimum near equator, as shown by the curve on figure 1. This curve, showing the fall-out rate during 1956 and 1957, is based on data obtained by radiochemical analysis. Data from soil analysis[12] and from gummed film measurements[10] give the same overall picture for fall-out deposit, although the peak in the northern hemisphere seems to be somewhat broader. The computation of a world-wide average of fall-out rate and deposit is rendered difficult by the existence of large areas not covered by surveys.[D103-109] It is clear, however, that the southern hemisphere has accumulated deposits that are lower than the average, while areas in the northern hemisphere (Japan, the United Kingdom, the United States) have deposits of about three times the world average.[10-15] It should further be pointed out that the large deviations from the average are towards the low side.

19. It has been reported that the fall-out rate in some countries shows seasonal variations,[13] apparently correlated with the known ozone fluctuations. This is, however, not supported by data from other countries.

II. Computation of external dose from fall-out deposit

20. The fall-out deposit contains gamma-emitters and is therefore an external source of radiation. The composition of the fission products and the corresponding gamma intensities change with time after an explosion. In the tropospheric component there is a large number of short-lived gamma-emitting isotopes and in the stratospheric component Cs^{137} is predominant.

21. It is impossible to make direct measurement of the very low exposure rate from fall-out except at areas close to test sites. Therefore, more indirect methods must be used.

22. To compute the exposure rate from deposited fission products, it is customary to assume that they are uniformly distributed over an infinite plane. The exposure rate from primary radiation is approximately independent of the distance above the ground, provided

Table I. Methods for collection and measurement of fall-out activity

Method	*Evaporation sampling (from pot collection)*	*Filtration and ion exchange*	*Gummed film*	*Gauze*
Collection	Rain water and dust	Rain water and dust	Dust	Dust
Area, approx. range in m^2	0.05 to 17	0.07 to 3.1	0.1	0.3
Time of collection	1 to 30 days or during precipitation, also 3 months' samples	4 to 30 days or during precipitation	1 day	1 day
Sample preparation and evaluation	The water is evaporated and the residue mounted for counting or first ashed or radio-chemically analysed.	The water is passed through paper, pulp, paper filter, anion exchanger and cation exchanger. The paper and the exchangers are separately ashed and mounted for counting.	The gummed film is ashed and the residue mounted on planchet or sealed between plastic films for counting.	The gauze is ashed and subsequently treated as the gummed film.
Efficiency of collection in per cent	100[a]	95[b]	63[c]	36[c]

[a] Assumed 100 per cent effective.
[b] Determined by measurement of effluent water.
[c] The pot collection method is used as reference.

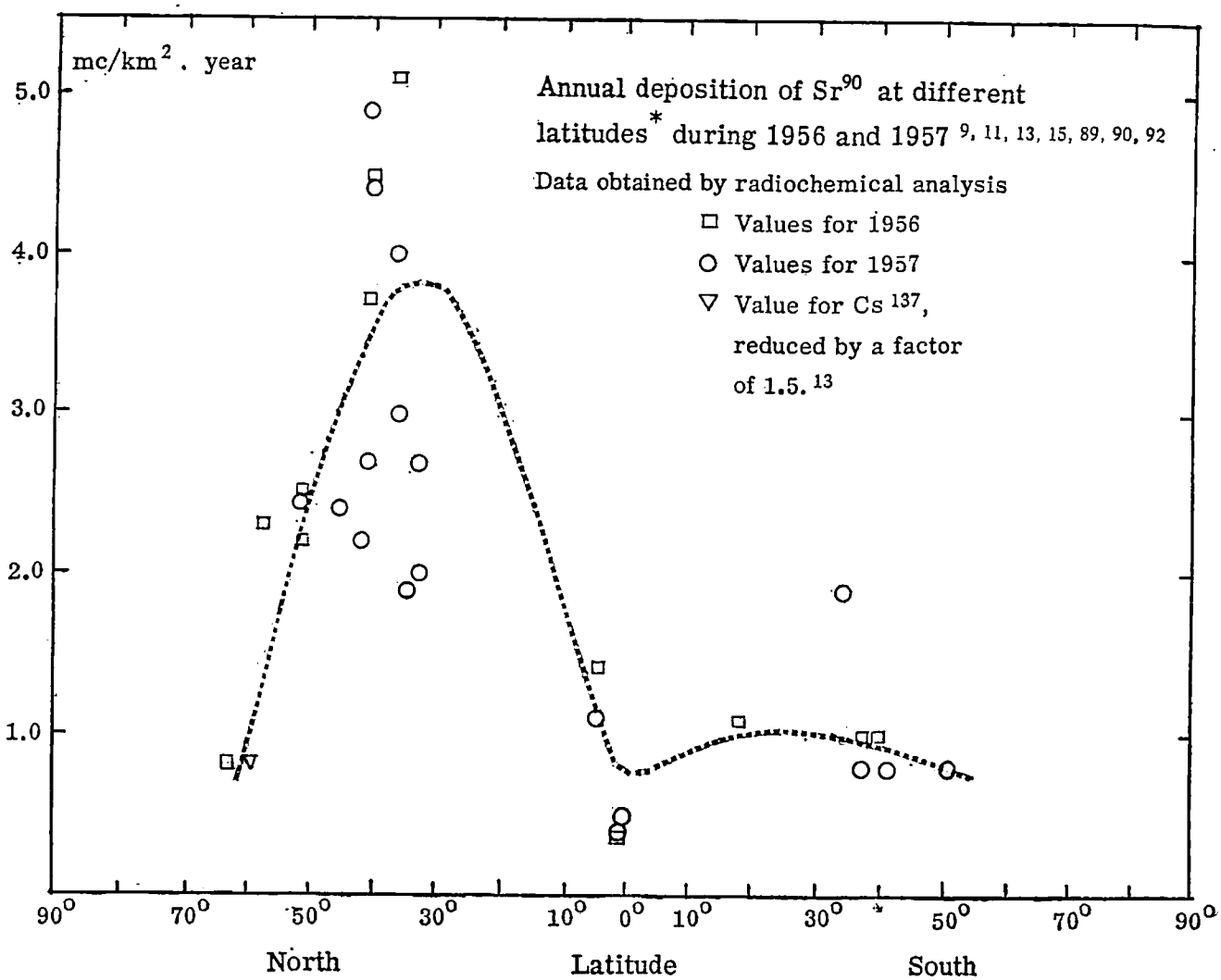

Figure 1. Meteorological factors for the different places of observation have not been taken into account

this does not exceed a few metres. One gets the expression:

$$I = c \times \bar{E}\gamma \times F_d^T(t) \qquad (1)$$

where

I is the exposure rate (mrad/year)

$c \approx 0.1 \quad \frac{\text{mrad.km}^2}{\text{year.mc.Mev}}$

$E\gamma$ is the average gamma energy emitted per disintegration (Mev)

$F_d^T(t)$ is the total activity of the deposit (mc/km^2)

This formula can be used for individual γ—emitters such as Cs^{137}, or for mixtures if $\bar{E}\gamma$ and $F_d^T(t)$ are known.

23. Two computation methods for the exposure rate from composite fall-out deposits have been used. One computation is based on measurements of total beta-activity of daily gummed film or rainwater samples.[16] This method has been shown to be reasonable at present even though the radioactive fall-out now is a mixture from several explosions.[10]

24. The other method takes into account that the exposure is derived from two components: (1) a "fresh" component of tropospheric origin and (2) a "long-lived" component (Cs^{137}) mainly of stratospheric origin.[17] It is shown that the 30-year dose** can be expressed with reasonable accuracy as:

$$D_{30} = aA_t + bA_{Cs137} \qquad (2)$$

where *a* and *b* are constants, A_t is the total beta activity (mc/km^2) and A_{Cs137} is the activity of Cs^{137} (mc/km^2). The values of the constants depend on the collection time and the time before the beta counting is done.

25. Values obtained for the infinite plane 30-year exposure due to fall-out deposited up to the end of 1957 are shown in table XIV and are of the order of 10 to 180 mr. The dose delivered to the gonad and bone marrow must be computed taking into account shielding, weathering and leaching factors. The shielding factor accounts for the reduced dose rate during the time the population spend indoors where the dose rate from fall-out deposit is reduced, whereas the weathering and leaching factors account for movement of the deposited gamma-emitting isotopes from the upper layers of the earth's surface, for example to lower layers of the soil. Taking all these effects into account, composite reduction factors ranging from 3 to 21 have been used in reports received by the Committee.[1,15,94,95] Using an average reduction factor of 10, the 30-year genetically significant

** The 30-year dose, which is approximately the genetically significant dose, is the dose received by an individual for the first 30 years of his life.

dose would be about 1 to 18 mrem. It should be emphasized that this is only the dose from what is already deposited, and that the total dose from what has been injected into the atmosphere will be higher, as discussed in paragraphs 94 to 115. Including the tropospheric component, the total dose from the external component will be of the same order of magnitude as the dose from fall-out isotopes taken up by the body.

III. Sr^{90} AS AN INTERNAL RADIATION SOURCE

26. Among the fall-out isotopes, Sr^{90} is of particular interest on account of the biological hazard that this isotope presents. Strontium is an element of the alkaline-earth group, and its chemical properties are in many ways similar to those of calcium, barium and radium. Thus Sr^{90} co-precipitates with calcium as phosphate or carbonate, and is included in the bone structure. Once included, Sr^{90} may remain in the bone structure for many years, the exact time not being known.[18] The osteocyte and bone marrow cells will be irradiated by the β particles from Sr^{90} and its daughter product Y^{90}. The ultimate question to be answered is the size of bone and bone marrow doses delivered by these isotopes.

27. To evaluate the present hazard from Sr^{90} the concentration in the bone must be determined. For hazard in the future, however, the change in this concentration, together with the concentration of Sr^{90} in different foodstuffs, should be determined. Of course, Sr^{90} primarily follows stable strontium through the food-chain, i.e., from the deposit on the ground, through uptake by plants and transfer through animals. For practical reasons, however, it is the calcium contributors to the national diet that are mostly studied.

Evaluation of Sr^{90} as an internal hazard

28. A Sr^{90} programme should attempt to take up the following problems:

(*a*) Amount of Sr^{90} so far deposited;
(*b*) Amount of Sr^{90} to be deposited;
(*c*) Rate of deposition of Sr^{90};
(*d*) As a result of (*a*), (*b*) and (*c*):
Eventual total accumulation of Sr^{90} on the ground;
(*e*) Kinetics of strontium in the biological cycle;
(*f*) Present bone level of Sr^{90};
(*g*) Future bone level of Sr^{90}.

To this end, the determination of Sr^{90} in the following materials is needed:

(*a*) Human bone;
(*b*) Components of the human food-chains;
(*c*) Fall-out materials (collected by the pot method);
(*d*) Air (atmosphere and stratosphere);
(*e*) Soils, grazing grounds and waters.

The determinations of stable calcium and strontium in the above-mentioned materials are of importance since their concentration is of value in interpreting the Sr^{90} results.

Sr^{90} in soil

29. Soil analysis is useful for the determination of accumulated Sr^{90}, as soil can be considered as a primary collector. For determination of fall-out rate, however, this method is not sufficiently accurate. In addition, the soil analysis has little value for the direct estimation of present Sr^{90} hazard owing to the difficulty of estimating the relative importance of the uptake of Sr^{90} in plants from soil and from foliage retention, that is, from uptake of Sr^{90} deposited directly on the leaves.

30. The extraction of Sr^{90} from the soil for analysis is difficult and many techniques are used, such as alkaline fusion, acid leaching, ammonium acetate leaching and electrodiolysis. The large amount of soil needed for analysis makes the alkaline fusion impracticable and the acid leaching method is very much preferred.[E13]

31. The upper 5 cm of the soil retain at present about 70-80 per cent of the deposited Sr^{90}, the exact value varying somewhat with the type of soil.[12,19-23] The total amount of Sr^{90}, as determined in different countries, is given in table II. Where only the upper 5 cm of the soil was analysed, a factor of 1/0.7 has been used to calculate the total amount. The numbers given are the average and the range of reported values. The values are in reasonable agreement with values for total deposit of Sr^{90} obtained by other methods of measurement.[5,11,13,15]

32. For the study of the behaviour of Sr^{90} in food-chains, it is useful to express the Sr^{90} concentration in activity per gram of available calcium.** The amount of calcium per kg of soil is extremely variable: for example, different areas in the United Kingdom show a range from 0.1 to 150 g calcium/kg soil,[22] although a small part only of the calcium is likely to be labile and available to plants in soils with the higher concentrations. Also, the available fraction of calcium is very variable; for example, in two different localities in the United States 3 and 42 per cent respectively of the calcium is available.[20] The availability to plants may also vary if its chemical form in the soil changes with time or under different conditions. Similarly the chemical form of stable strontium will influence its availability to plants.

Sr^{90} in food-chains

33. From the environment to the human skeleton, strontium follows a long path accompanying calcium. The problems to be considered are the transfer of Sr^{90} and stable strontium in food-chains and the transfer from soil to plant.

Discrimination factors

34. The chemical similarities between strontium and calcium make the use of Sr^{90}/calcium ratio convenient for following Sr^{90} from the environment to human

** For concentrations of Sr^{90} the unit 1 micro-microcurie ($\mu\mu$c) Sr^{90} per gram calcium is used (1 strontium unit, 1 S.U.).

TABLE II. AMOUNT OF Sr^{90} IN SOIL

Country	Japan[23]	Sweden[9]	UK[22, 89]	USA[20, 88]	USSR[5]
Period of measurement	January–May 1957	Mid-1956	July 1957	October 1957	February–July 1957
Sr^{90} in mc/km^2	2.5–6.3	1.2[a] (0.6–2.0)	5.3 (3.5–14.5)	9.7 (3.2–13)	6.0 (3.0–12)

[a] These preliminary data are probably too low, as an ammonium acetate leaching method was used for the extraction of Sr^{90} from soil.

TABLE III. DISCRIMINATION FACTORS

Species	*Diet*	*Method*	*Remarks*	*Classification*[a]	*Value*[b]	*Reference*
Man.....	Milk	Double tracer with each meal	4 patients, 9 to 73 years old	Diet → bone	0.54 (0.50–0.62)	29
Man.....	Normal mixed	Stable Sr/Ca ratio in diet and bone	Average adult diet in U.K.	Diet → bone	0.25	30
Man.....	Normal mixed	Stable Sr/Ca ratio in diet and bone	Average diet in Canada	Diet → bone	0.5	48, 91
Man.....	Normal mixed	Stable Sr/Ca ratios	1 normal	Diet → bone	0.24	31
Man.....	Non-milk	Double tracer with each meal	4 patients	Diet → bone	0.44 (0.37–0.51)	29
Man.....	Non-milk	Double tracer, single dose	2 patients	Diet → bone	0.35 (0.25, 0.45)	32
Man.....	Normal mixed	Sr^{90}/Ca ratio in diet and bone	Indirect calculation	Diet → bone	0.25	33
Man.....		Stable Sr/Ca ratio in diet and bone (disregarding marine contribution to diet)	Average Japanese diet and average bone concentration	Diet → bone	0.17	34
Sheep.....	Grass from uncultivated pasture	Stable Sr/Ca ratio in grass and bone	6 animals	Diet → bone	0.24 (0.15–0.31)	22
Sheep.....	Grass from uncultivated pasture	Sr^{90}/Ca ratio in grass and bone	6 animals	Diet → bone	0.23 (0.09–0.42)	22
Goat.....	Non-milk	Double tracer, daily dose	2 animals	Diet → bone	0.23	35
Rat.....	Milk	Double tracer in dietary		Diet → bone	0.57±0.02	28
Rat.....	Non-milk	Double tracer in dietary		Diet → bone	0.27±0.01	28
Rat.....	Non-milk	Lifetime feeding of radiostrontium/Ca		Diet → bone	0.28	27
Rat.....	Non-milk	Stable Sr/Ca ratios		Diet → bone	0.27	27
Mouse.....	Non-milk	Stable Sr/Ca ratios		Diet → bone	0.35	27
Guinea pig.....	Non-milk	Stable Sr/Ca ratios		Diet → bone	0.22	27
Jack rabbit.....	Natural (on desert)	Stable Sr/Ca ratios		Diet → bone	0.20	27
Cottontail rabbit	Natural (on desert)	Stable Sr/Ca ratios		Diet → bone	0.22	27
Kangaroo rat...	Natural (on desert)	Stable Sr/Ca ratios		Diet → bone	0.16	27
Cow.....		Radiostrontium and radio-calcium at different times		Diet → milk	0.14	36
Cow.....		Sr^{90} assay of Wisconsin milkshed, 1953		Diet → milk	0.16	37
Cow.....		Sr^{90} assay of Wisconsin milkshed, 1955		Diet → milk	0.16	21
Cow.....		Sr^{90} assay in U.K., 1955		Diet → milk	0.09	26
Goat.....		Double tracer, daily dose 2 animals 13 days		Diet → milk	0.09 (0.08, 0.10)	35
Rat.....		Double tracer in dietary		Plasma → foetus	0.55–0.65	38
Rabbit.....		Double tracer in dietary		Plasma → foetus	0.49	38

[a] Although some of the following discrimination factors are determined as $DF_{(diet \rightarrow blood)}$, they have been written $DF_{(diet \rightarrow bone)}$, as $DF_{(blood \rightarrow bone)}$ is very near unity.[28, 35, 39-42]

[b] The range or mean ± standard error is given where available.

bones. However, the chemical behaviours of strontium and calcium are not identical and, therefore, their utilization varies in biological processes such as assimilation and milk secretion. For example, cows utilize calcium more efficiently than strontium in producing milk. To express quantitatively the preferential utilization of one of these elements in a given process, the following nomenclature is proposed:

$$\text{Discrimination factor}^{\dagger}\ DF_{(\text{precursor}\rightarrow\text{sample})} = \frac{\text{Sr/Ca ratio in sample}}{\text{Sr/Ca ratio in precursor}}$$

This discrimination between strontium and calcium is caused by several physiological factors among which the most important are: preferential absorption of calcium from the gastrointestinal tract; preferential urinary excretion of strontium; preferential secretion of calcium from blood into milk and preferential transfer of calcium across the placental barrier. The quantitative evaluation of the contributions of these physiological processes has been made under certain conditions.[24] It is possible to define an over-all discrimination factor for a given food-chain as the product of the discrimination factors for each step of the chain, under the condition that there is no additional entrance of strontium or calcium from other sources into any of the intermediate steps. For example, in the chain: soil → grass → cow's milk → human bone, the over-all discrimination factor is:

$$DF_{(\text{soil}\rightarrow\text{bone})} = DF_{(\text{soil}\rightarrow\text{grass})} \times DF_{(\text{grass}\rightarrow\text{cow's milk})} \times DF_{(\text{cow's milk}\rightarrow\text{human bone})}.$$

35. Various methods have been described for measuring the discrimination factors:

(*a*) By measuring the stable strontium/calcium ratio in precursor and in sample;[25]

(*b*) By measuring the radiostrontium/calcium ratio, for example Sr^{90}/calcium in precursor and in sample in equilibrium, either under field conditions[22,26] or in dietary experiments;[27]

(*c*) By double tracer experiments, for example, using Ca^{45} and Sr^{85}.[28]

36. In the case of Sr^{90} transfer from fall-out deposit to human bone, the problem is complicated at present by the possibility that the human bone may often not be in equilibrium with the environment. The discrimination factors obtained by technique (*a*) give inherently the equilibrium value and this technique is therefore very important for the evaluation of future risk. For this reason, the determination of stable strontium and calcium in the steps of the food-chains is fundamental. It is important, however, that the subjects have lived on a diet with a constant stable strontium/calcium ratio and that the entire diet is analysed. Some values for discrimination factors are summarized in table III and in paragraph 47.

The soil-vegetation step in food-chains

37. It is very difficult to compute an over-all discrimination factor for the soil-vegetation step. The plants receive Sr^{90} from soil through the roots and also directly from fall-out deposited on the leaves and the concentration may not be uniform throughout the plant.[19,20] With information available at present it is difficult to estimate the relative importance of the two routes of entry as:

(*a*) The accumulated deposit is at present increasing, whereas the fall-out rate has been approximately constant for the last four years.[D104]

(*b*) The mechanism of deposition (dry fall-out, continuous slow precipitation, heavy showers) may change the efficiency of foliar retention.

(*c*) The type and condition of the foliage may change the efficiency for retention of direct deposit.

(*d*) There are great differences in the growing periods and, therefore, in the exposure time of different plants.

(*e*) The accumulation of fission products at the stems of plants may influence the relative significance of the two factors, as this accumulation will depend on the fall-out rate for some previous years.[D44]

(*f*) There are indications that in soils with low available calcium contents, the root uptake of Sr^{90} is more important than in soils with more available calcium.[D44]

(*g*) The depth of the root penetration, the soil type, the water supply and the depth of ploughing may change the root uptake.

38. For the indirect evaluation of the relative importance of the two components, both stable strontium and calcium data are useful. A possible approach is based on the measurement of the specific activity of Sr^{90} in plant and in soil ($\mu\mu c\ Sr^{90}$/g stable strontium). As the Sr^{90} retained by the foliage is carrier-free the ratio:

$$\frac{\text{specific activity of } Sr^{90} \text{ in soil}}{\text{specific activity of } Sr^{90} \text{ in plant}}$$

gives the fraction of the total Sr^{90} in the plant that comes from soil. If the specific activity of the soil is computed from the total strontium content and not from the amount of strontium available to the plant, this fraction will represent a lower limit, and the available strontium may in certain circumstances represent a small proportion only of the total strontium.

39. An experiment has been reported on the direct determination of the surface contamination of grain of the 1956 harvest in the Soviet Union. The grain was washed with 0.5 per cent hydrochloric acid and water, which removed at least 50 per cent of the total Sr^{90}.[5]

40. Another approach to the problem depends on a direct correlation of the rate of deposition of Sr^{90}, the accumulated deposit and the Sr^{90} content in any particular food. This has been attempted for milk[43] in the following way, taking yearly averages to avoid seasonal effects, and assuming that the Sr^{90} in milk comes from the following sources:

(*a*) Uptake by vegetation through the roots, assumed to be proportional to the accumulated deposit in soil (F_d, in mc/km^2, the value at the beginning of the one-year period):

(*b*) Direct deposits on leaves, assumed to be proportional to the fall-out deposit in a one-year period (f_d, in mc/km^2).

The average St^{90} level in milk in a one-year period C_M is then given by:

$$C_M = a_M(F_d + 1/2f_d) + b_M f_d \qquad (3)$$

where a_M and b_M are proportionality constants.

41. Using data from Perry, N. Y., U.S.A., a set of constants a_M and b_M can be computed. The values for F_d and f_d are estimated from New York City pot data corrected by a factor derived from gummed film data from places near Perry and in New York City.

† A system of nomenclature has been earlier proposed[24]; in this system the term "Observed Ratio" (OR) was proposed for the over-all discrimination between a precursor and sample and the term "Discrimination Factor" was used to denote the discrimination that is produced by a given physiological process.

TABLE IV. Sr^{90} DATA FROM PERRY, N. Y., U. S. A.

Period	Sr^{90} in milk, S.U.	F_d, deposited Sr^{90} in mc/km²	f_d, annual Sr^{90} deposit, mc/km²,
April 1954–March 1955	1.20	0.89	2.30
Jan. 1955–Dec. 1955..	1.89	2.16	2.78
Oct. 1955–Sept. 1956..	2.86	4.57	3.36
July 1956–June 1957..	3.94	7.48	3.58

From these data one calculates the constants: a_M = 0.34 S.U. km²/mc and b_M = 0.23 S.U. km²/mc.*

42. In the milk from the four one-year periods, the fractions of Sr^{90} derived from foliar retention are 43, 35, 27 and 21 per cent respectively of the total Sr^{90} content. These fractions need not necessarily be measures of the foliar retention of the plants, as the relative contribution may have been altered by factors such as washing of the grass by rain, and differences in chemical form of the Sr^{90} that the plants had obtained from the two origins. It is likely also that values of a_M may vary with time if the chemical state of radiostrontium in the soil changes progressively.

43. To determine the root uptake directly, crop experiments have been performed in the United Kingdom with Sr^{89} tracer.[96] With the conditions of soil and cultivation in that country, concentration of 1.1 S.U. in grass was found for an accumulated level of 1mc/km² from root uptake alone.[44] This corresponds to a milk concentration of about 0.15 S.U., derived by using the appropriate discrimination factor from table III.[D36] The constant a_M in equation (3) should thus have a value of about 0.15 S.U. km²/mc for the United Kingdom as derived from experiments lasting for one year with Sr^{89} well equilibrated with soil. Experiments also indicate a foliar retention ranging up to 90 per cent of the total herbage contamination.

44. For other food materials and crops, a method similar to that given in paragraph 40 is applicable with three provisions:

(*a*) The relevant period during which the fall-out is averaged should in some cases be limited to the growing period of the plant if this is much shorter than one year, although the fall-out during this period may correlate with the annual fall-out rate.

(*b*) Some plants have leaves at the base of the stem, or a horizontal mat of roots, which may persist for several years and prevent the Sr^{90} fall-out from passing to the soil. If the growing parts of the plant derive Sr^{90} from such a persistent stem base or root mat, the appropriate averaging period for the fall-out rate may need to be several years. Since, at the present time, the fall-out deposited during the last four years is nearly equal to the total fall-out deposit, the formula given above may fail to distinguish between uptake from a stem base or root mat on the one hand and from the accumulated deposit present in the soil on the other.

(*c*) The uptake of Sr^{90} from the soil is likely to be influenced somewhat by the amount of available calcium in the soil. There are indications that in soils which are very deficient in available calcium, the root uptake of Sr^{90} may be greater than from high total calcium soils,[22] and that on such soils the possible formation of root mats may also enhance the uptake. The foliar uptake of Sr^{90} is not, however, influenced in this way by soil calcium. The proportions of Sr^{90} taken up through leaves and through roots will therefore depend on the calcium status of the soil as well as upon the type of plant, conditions of culture and the rate and quantity of Sr^{90} fall-out. It should be emphasized, however, that the Sr^{90} uptake of plants from soil is effected not only by the absolute quantity of calcium present, but also by the degree of saturation of the colloidal complex of the soil by calcium and other cations, such as magnesium, potassium and sodium, and this varies materially from one soil to another.[45]

45. In the important case of rice, the outer layers of the grain become contaminated by carrier-free Sr^{90} deposited on them from fall-out occurring during a very short period before the harvest. The kernel of the grain has an Sr^{90} uptake which appears to be more dependent upon accumulated deposit than upon rate of fall-out;[23] this will be accentuated by the shortness of the growing period, by the ploughing of each season's straw into the upper soil layers and also by the formation of a root mat under certain conditions of growth. The Sr^{90} content of white rice is thus mainly dependent on root uptake, whereas that of brown rice, from which the outer layers have not been removed, is at present more dependent on surface contamination.

46. To distinguish between the amount of Sr^{90} reaching plants through their roots, as compared with that coming from foliar absorption or uptake from the stem base, is important for predicting their relative significance under future conditions. If, in the future, the accumulated deposit of Sr^{90} in the soil has increased considerably relative to the fall-out rate, the relative uptake of Sr^{90} from the soil is likely to become much greater than that by other routes, especially for soil of very low calcium content. Forecasts of plant contamination under such future conditions can, therefore, only be based adequately upon that component of present uptake which depends on the accumulated deposit of Sr^{90}.

47. From the preceding paragraphs it may be deduced that an evaluation of a generally valid discrimination factor that includes the step from soil is very difficult at best. For defined conditions, however, some values have been reported. Thus $DF_{(soil \rightarrow diet)}$ has been estimated as 0.5, based on values for stable strontium/calcium ratios in average Japanese soil and diet.[34] Data obtained in the United States indicated that $DF_{(soil \rightarrow plant)}$ may be about unity.[46] A general approach, by using stable strontium/calcium ratios in average rock and soil and in human bones, has given the value 0.07 ± 0.01 for $DF_{(soil \rightarrow human\ bone)}$,[47] although this value will vary according to the type of diet.

Concentrations of Sr^{90} in foodstuffs

48. Data submitted to the Committee on concentrations of Sr^{90} in different foodstuffs are collected in table XVI. The data show a wide range, caused both by geographic and seasonal effects. Only selected data are therefore meaningful if one wants to examine the increase of the concentration with time. Some such data for milk are collected in table V. Analysis has shown that dried and fluid milk and cream and skimmed milk from the same whole milk sample have the same Sr^{90}/calcium ratio.[48]

49. Cereals and vegetables, as a rule, show higher concentrations of Sr^{90} than milk and milk products, as shown in table VI.

Calcium sources in diet

50. If the dietary habits of a population are known with respect to the main sources of calicum and also the

* The values given in reference 43 were calculated using experimental data from a shorter period. They differ by about 10 per cent from the values above.

concentration of Sr^{90} in the various foodstuffs, the daily uptake of Sr^{90} from vegetation to human bone can be computed, using discrimination factors for the different steps in the food-chains as given in table III.[D36] Table VII, submitted by the Food and Agriculture Organization in consultation with the World Health Organization, gives some data on dietary habits in different countries. Additional data from some of these countries support the values.[23,30,34,52] It should be pointed out that there are only a few countries from which suitable data were available.[51]

TABLE V. AVERAGE CONCENTRATION OF Sr^{90} IN MILK (IN S.U.) IN SOME SELECTED AREAS

Location	*1954*	*1955*	*1956*	*1957*	*Reference*
Canada					
6 stations[a]			5.0	6.2	48, 49
U.K.					
Somerset[b]		4.1	4.4	5.1	22, 30
U.S.A.					
Perry, N. Y. (Jan.–Dec.)		1.9	3.3	3.9	92
(Apr.–Dec.)	1.1	2.2	3.7	4.0	
New York City (Jan.–Dec.)		2.7		4.5	92
(June–Dec.)	1.4	3.7		5.0	
State College, Miss. (May–Sept.)		3.8	4.8		92
Columbus, Wisc. (Jan.–Oct.)			3.7	4.2	92
(May–Oct.)		2.6	4.0	5.3	
Mandan, No. Dak. (Jan.–Dec.)			9.2	16	92
(May–Dec.)		7.2	9.1	22	

[a] Monthly data for each station are compared with data from the same month in the two years, altogether 57 values used.
[b] Median values.

TABLE VI. CONCENTRATIONS OF Sr^{90} IN (S.U.) IN CEREALS AND VEGETABLES

Location and type of sample	*1956*	*1957*	*Reference*
Japan			
Rice, white	49 (36,62)		23
Rice, brown	154 (81–250)		
Wheat, flour		53	
Wheat, brown		162 (153,170)	
Soviet Union			
Wheat and rye	69 (28–140)		5
United Kingdom			
Vegetables		11 (6–35)	30
United States			
Different cereals	14 (4–38)		
Vegetables[a]	8 (1–29)	9 (1–23)	33, 50

[a] The samples were frozen vegetables from food plants.

TABLE VII. SOME PRINCIPAL SOURCES OF CALCIUM IN THE AVERAGE DIETS OF A FEW SELECTED COUNTRIES[51]

Country	*Per capita average daily intake, mg calcium*		
	Cereals, vegetables, etc.	*Milk and milk products*	*Fish and marine products*
Argentina	84	510	–
Australia	52	570	12
Canada	109	780	–
Japan	264	20	106
Philippines	53	32	–
Union of South Africa	56	260	7
United Kingdom	370	585	12

51. The data in table VII should only be taken to indicate the order of magnitude of the calcium supplies in the different countries. The main contribution to the human diets vary widely from one country to another, and there are wide variations within the same country in accordance with many general and local differences in food supplies, dietary habits and economic conditions.[51] Milk and milk products are the major source of calcium intake in most Western countries (giving about 70-85 per cent of the total calcium), whereas they play a very minor role in most of the countries in Asia and Africa, where other foods such as cereals, vegetables and also fish and marine products are the principal sources of calcium in the average diets. Moreover, certain foods not originally rich in calcium are fortified by mineral calcium in many countries.

Stable strontium sources in diet

52. Some data on the content of stable strontium in various types of food are also available and are summarized in table VIII.

TABLE VIII. AVERAGE STABLE STRONTIUM CONTENT IN VARIOUS TYPES OF FOODS

Type	*mg Sr/gCa*	*Reference*
Cereals and vegetables	2	22, 23
Milk and milk products	0.3	20, 22, 48
Marine fish	3	23
Fresh water fish	1	23

These data show that the stable strontium/calcium ratio of certain foods may be up to ten times higher than in milk and milk products. Therefore milk may not be the main source of stable strontium in diet although it may be the main source of calcium (see table IX).

Daily intake of Sr^{90} in man

53. Daily intake of Sr^{90} has been reported from some places. Table IX shows data from the United Kingdom, together with data on stable calcium and strontium intake.

TABLE IX. AVERAGE DAILY INTAKE OF CALCIUM, STABLE STRONTIUM AND Sr^{90} IN ADULT DIET IN UNITED KINGDOM[30]

Food	*Calcium intake, mg/day*	*Stable strontium intake, µg/day*	*Sr^{90} intake µµc/day*
Milk	667	193	3.64
Flour and bread[a]	332	714	0.66
All other foods	200	526	2.35
TOTAL	1199	1433	6.65

[a] Fortified with mineral calcium.

54. Wide variation can be expected because of different food habits and living conditions, as illustrated by computations from Japan.[34] They show that whereas the majority of the population have an average daily intake of 3.3 to 5.8 µµc Sr^{90} per day, there is a substantial number of people, who either eat unpolished brown rice or drink and prepare food with unfiltered rainwater, which may cause a daily intake of 23 to 26 µµc Sr^{90} per day.

Sr^{90} in human bone

55. The measurements of Sr^{90} concentrations in human bone give the data that are most needed for the estimation of present risks from fall-out. The interpretation of bone Sr^{90} results is complicated by four important factors, which will be discussed in the following paragraphs.

(1) Due to lag in contamination of calcium sources with Sr^{90}, human bone is not yet in equilibrium with the environment. To correlate the Sr^{90} content of human bone with the contamination level of the environment and to predict future risks, it is necessary to know how close the system bone-environment is to equilibrium. For this purpose stable strontium measurements are very useful.

(2) If Sr^{90} were unevenly distributed in the human skeleton the measurement of a single bone would not be representative of the average skeleton value.

(3) Uneven distribution of Sr^{90} within the bone would also make the relevant dose computation difficult.

(4) The average Sr^{90} content of bone may also vary with age.

The importance of the stable strontium determination

56. Using the stable strontium/calcium ratios in different steps of the food-chains and in bone, it is possible to determine the discrimination factors[D35] and compute the equilibrium concentration in bone. The determination of stable strontium in bone can be done by spectography[47,53,54] or by activation analysis.[55,56] The reported values differ somewhat, and this may partly be explained by a small but significant difference observed from one locality to the next.[47] An average of 450 $\pm$ 100 μg strontium/gram calcium has been found using 756 samples from all over the world.[47] Investigations in Canada and the United Kingdom have given average values from 290 to 370 μg strontium/gram calcium using a limited number of samples (16 to 35).[22,49,50] Young children apparently have somewhat lower strontium concentrations in bone than adults,[22,56] which should be expected as a result of foetal discrimination against strontium.[38]

Sr^{90} distribution in different bones of the skeleton

57. The problem of non-uniformity in the distribution of stable strontium in different bones in the skeleton of man has also been investigated by stable strontium measurements. It seems that there is a uniform distribution,[47,56] which should mean that the distribution of Sr^{90} should also be uniform when the skeleton has reached equilibrium with a contaminated environment. This has been confirmed for goats fed by Ca^{45} and Sr^{89} over an extended period,[35] and by measurements on the distribution of Sr^{90} in cow's bones.[48] In man, however, there are experiments showing non-uniformity by single injections of double tracers and also in the Sr^{90} distribution at present in adults.[33,57]

Uniformity of Sr^{90} distribution in bone

58. It seems clear that Sr^{90} would be distributed uniformly with calcium throughout the bones of a child whose calcium intake had been contaminated with Sr^{90} at constant concentration during the whole of its life since, in these circumstances, all bone formed would be derived from calcium of equal Sr^{90} content.

59. Non-uniform deposition would arise from two main causes:

(*a*) A progressive change in the Sr^{90} contamination of dietary sources will lead to a corresponding change in Sr^{90} level of new deposits of bone, which contain the most sensitive cells. With rising dietary levels, the bone concentrations in young children will indicate the current dietary conditions. Much of the bone of older children and of adults will, however, be contaminated at lower levels corresponding to the lower levels in diets of earlier years. In this sense, the maximum bone concentrations in young children may be in equilibrium with their current diet, although the amount of bone contaminated at this concentration may well be only a fraction of the whole skeleton. Correction for non-uniformity of Sr^{90} distribution is not, however, required if the concentration in young children is used as an indication of the maximum concentrations being reached in new bone deposited in older children or adults.

(*b*) Any change in source of calcium intake may involve an alteration of Sr^{90} level in this intake and thus in bone that is currently being formed. An important instance arises in young children, whose bone calcium will have been derived from three different sources:

(i) From the mother during gestation;

(ii) From the mother's milk during maternal feeding;

(iii) From the subsequent dietary sources.

60. Some indication may be given as to the importance of these factors. Calcium derived during gestation appears at present to be somewhat lower in Sr^{90} levels (about one half) than the child's subsequent diet, since the level in the bones of stillborn children is rather less than in children 1 to 2 years old (table X). The Sr^{90} content of the bones of a child of 2 years would be only slightly lowered for this reason since at this age only about 15-20 per cent of the bone calcium and associated Sr^{90} will have been derived during gestation.[58]

61. Maternal milk contains about 40 per cent of the level of Sr^{90} in the diet of the mother.[93] Since about 25 per cent or less of the bone of a 2-year-old child, previously breastfed for half a year, will have been derived from maternal milk, this factor would only lower the average bone Sr^{90} level by about 15 per cent or less from an equilibrium condition with the diet.[58]

62. Thus the highest radiation doses delivered to bone from radiostrontium are likely to be those in the new bone, that is at present being laid down in children aged over 1 year. If the concentration remains constant, the absolute quantity of strontium in the body increases with the size of the skeleton up to 20 years, and on the assumption of a linear dose effect relationship, the probability of somatic mutation in bone-marrow cells increases with the size of the skeleton.

The problem of computing skeleton dose from Sr^{90}

63. As a first approximation, Sr^{90} will be considered to be uniformly distributed in the skeleton and it will be assumed that the whole radiated energy is absorbed by the bone. The mean particle energy of the pair Sr^{90} and Y^{90} is 1.13 Mev[59], so that a skeleton containing 1g calcium per 7g bone will receive an average dose rate in compact bone of 2.7 mrem/year per strontium unit.[60] In the skeleton about 10 to 13 per cent is spongious bone, having a dose rate of about 0.9 mrem/year per strontium unit. The average dose rate to the compact and spongious bone of 2.5 mrem/year will be used in the following calculations.[61,62]

64. The bone marrow dose from Sr^{90} deposited in the bone will be lower than the bone dose, depending on the size of the marrow cavity. A calculation of a mean marrow dose is therefore a very complex problem.[60-62] In the following it will be assumed that 1 strontium unit will cause a mean bone marrow dose rate of 1 mrem/year. The true value of the mean marrow dose** might

** The computation of the mean marrow dose is difficult and approximate only.

TABLE X. AVERAGE CONCENTRATION OF Sr^{90} IN MAN (STRONTIUM UNITS)[a]

Age Group	Canada[48, 49] 1956–1957	United Kingdom[22, 59] 1956	United Kingdom[22, 59] 1957	United States[21, b] 1955–1956	United States[21, b] 1956–1957
Stillborn to 1 month	0.7 (3)	0.44 (5)	0.55 (42)		
1 month to 1 year	1.6 (2)	0.70 (11)	1.1 (19)		
1 year to 5 years	2.1 (4)	0.83 (13)	1.2 (17)	0.56 (10) [c]	0.67 (30) [c]
5 years to 20 years	0.1 (1)	0.25 (12)	0.45 (19)	0.26 (17)	0.54 (32)
More than 20 years	0.4 (3)	0.11 (5)	0.1 (4)	0.07 (137)	0.07 (62)

[a] The number of samples in each age group is given in parentheses.

[b] Including a few data from North America outside the United States.

[c] Age group 0 to 5 years.

however, be as low as 0.5 or as high as 2 mrem/year per strontium unit.*

65. It should be emphasized that bone marrow cells which are almost surrounded by bone will receive doses which may be equal to those in compact bone. Taking into account all causes for non-uniformity, i.e. the non-uniform deposition in the mineralized zones, the variation in bone layer widths and geometrical factors (corners), the bone marrow level is probably five times the figures quoted above.

Concentration of Sr^{90} in man

66. The knowledge of average values is not sufficient for risk evaluation and individual data are extremely useful. It is emphasized that data on bone concentrations should be accompanied by the following information:

(*a*) Date of death or biopsy;

(*b*) Age at death or biopsy;

(*c*) Precise origin:

(*d*) In case of children: methods of feeding.

67. Not all the data obtained so far include complete information, and further studies are required. Table X gives some of the bone concentrations measured in different countries (see also table XVII).

IV. Cs^{137} AS AN INTERNAL SOURCE

68. The similarity between the nature of the precursors, half-lives and fission yields of Sr^{90} and Cs^{137} suggests that the distribution of these two isotopes is similar in fall-out. On the other hand, their different chemical properties make their behavour in food-chains and in the body different.

69. Cs^{137} is poorly taken up from soil by plants.[19,64,65] Therefore, the contamination of food sources should depend largely on fall-out rate. The biological half-life of caesium is comparatively short (about 140 days in man[65] and 20 days in cow[66]), thus indicating that the level of the isotope in the human body will approach equilibrium with the environment relatively quickly.

70. Cs^{137} concentrations are often expressed by the Cs^{137}/potassium ratio. Some evidence exists, however, that the metabolism and routes of entry into the human body of these elements are to some degree different. For example, in man, the biological half-life of potassium (35 days)[67] is apparently shorter than that of caesium. An analogy of Sr^{90}/calcium ratios should therefore not be implied.

Methods for measurement of concentrations of Cs^{137}

71. Measurements of concentrations of Cs^{137} can be made without radiochemical separations. Cs^{137} has a gamma-emitting daughter product, Ba^{137}, which can be determined using gamma-spectroscopy, as can K^{40}.[E15] The large difference in energy of the gamma rays emitted from Cs^{137} (0.66 Mev) and K^{40} (1.46 Mev) makes the discrimination adequate even with crystal detectors of low energy resolution. Radiochemical methods are also in use for separation of caesium from other material.[E15]

72. The present burden of Cs^{137} in man can be determined *in vivo* with whole body spectrometry or gamma spectroscopy.[E15] Large liquid scintillators have the advantage of being geometrically efficient, but the energy resolution is relatively poor. Sodium iodide crystals have good energy resolution, but even with the largest crystals available, the counting rate is not as high as with the large liquid scintillators. To obtain the maximum of information, both types of counter seem necessary.[68]

Concentration of Cs^{137} in foodstuffs

73. As in the case of Sr^{90} it should be possible to relate the Cs^{137} burden in man to the concentration in the diet. In some areas (i.e. the United States), milk contributes about 50 per cent of the human uptake[65] and can therefore be used for comparative purposes. During 1956-1957, milk in different countries showed a general Cs^{137} concentration of 20 to 70 $\mu\mu$c Cs^{137}/g potassium.[23,65,73,74,86,87] The wide range is partly caused by variation with geographic locality. Measurement of rice in Japan 1956-1957 showed a concentration of about 50$\mu\mu$c Cs^{137}/g potassium.

Daily intake of Cs^{137} in man

74. Estimations of daily intake of Cs^{137} have been made for Japan and the United States, giving about 30 to 50 $\mu\mu$c Cs^{137}/day.[23,65] Because of the short biological half-life for Cs^{137}, variations in the diet will change the Cs^{137} level in man rapidly. With the constant concentration in the diet, the equilibrium burden in man is reached in about two years.

Concentrations of Cs^{137} in man

75. The measurements of Cs^{137} in man show a range of 25 to 70 $\mu\mu$c Cs^{137}/g potassium in the north temperate zone during 1956-1957 with an average of about 35 $\mu\mu$c Cs^{137}/g potassium.[65,69] During periods shortly after tests, a slight increase has been observed.[65] Concentrations in the diet and in man are apparently rather similar, which is unexpected because of the longer biological half-life of caesium as compared to potassium.[65]

Dose rate from Cs^{137} in man

76. Since the average potassium content of a standard man (70 kg body weight) is about 150 g,[67,69,70] the average Cs^{137} gonad dose rate amounts to about

* Higher mean marrow doses are possible and higher doses in small foci of bone can be expected.

1 mrem/year (ranging from about 0.5 to 2 mrem/year).[65] Uniform distribution of caesium in soft tissue is assumed as is indicated by stable caesium measurements.[71]

V. Doses from tropospheric fall-out

77. Fall-out from the troposphere consists mainly of short-lived isotopes and the dose contributions are therefore primarily dependent on fall-out rate rather than on accumulated deposit. The latitudes where the tropospheric fall-out is deposited are mainly determined by the latitude of the test sites. The doses from tropospheric fall-out material vary with geographic location roughly in the same manner as the dose from stratospheric fall-out.

External Sources

78. The tropospheric material has an observed mean residence time of two to four weeks[1] and although it is deposited intermittently during the year, a certain deposit of short-lived activities is built up and maintained. The reported values indicate that a level of short-lived radioactivity is maintained at about 50 to 200/mc/km^2 (See table XIV). Allowing a factor of 10 for shielding and weathering and assuming an average γ-energy of about 0.5 Mev[16], the annual gonad and mean bone marrow dose should be of the order of 0.25 to 1 mrem/year.[D22]

Internal Sources

79. The air concentration of fission products at ground level has been reported to be about 10^{-15}c/l during 1956 to 1957 (See table XVI). Assuming that this material has the same composition as the fall-out, the annual dose resulting from inhalation has been computed[72] using data for retention, volume of inhaled air, weight of critical organs, etc., based on I.C.R.P.—criteria.[67] The annual doses, according to the calculations, are:

Whole body dose	0.2	mrem
Lung dose (if material soluble)	0.1	mrem
(if material insoluble)	1.5	mrem
Thyroid dose	0.6	mrem
Bone dose (Sr^{89}, Sr^{90}, Ba^{140})	0.15	mrem
Average bone marrow dose (Sr^{89}, Sr^{90}, Ba^{140})	0.05	mrem
Average gut dose	0.03	mrem

Sr^{90} and Ba^{140} as internal sources

80. Dose contribution from short-lived activities can be introduced through food-chains when the food has not been stored for a long time. Storage of food reduces the activity of short-lived isotopes, which makes it very difficult, if not impossible, to give world-wide average annual doses from tropospheric material.

81. It has been reported that Sr^{89}/Sr^{90} activity ratios in milk show fluctuations in the range 1 to 25.[20,22,48,49,73,74] There are marked seasonal variations, largely dependent on whether the cows were on pasture. Thus the average Sr^{89} concentration in milk has been reported as 3 to 12 $\mu\mu$c Sr^{89}/g calcium in January to April, whereas it was of the order of 100 to 150 $\mu\mu$c Sr^{89}/g calcium in September and October in Canada in both 1956 and 1957. The Sr^{90} concentration was all the time of the order of 4 to 8 $\mu\mu$c Sr^{90}/g calcium.[48,49]

82. Computation of the relative doses from the two isotopes, using the range of values observed in milk for the Sr^{89}/Sr^{90} ratios, show that the doses from Sr^{89} give rise to a bone dose ranging from about 1 to 20 per cent of that from Sr^{90}.† Ba^{140} in the amount that corresponds to the mean residence time of the tropospheric fall-out (3 weeks), gives a dose contribution that is less than 10 per cent of the dose from Sr^{89}.

83. Data from measurements in Canada, show the presence of Sr^{89} in bone from man and animals, as given in table XI.

TABLE XI. CONCENTRATIONS OF Sr^{89} AND Sr^{90} IN BONE[48]
($\mu\mu$c per g calcium)

Sample and date of death	*Age*	*Sr^{89}*	*Sr^{90}*
Human bone			
December 1956	5 months	5.4±0.6	1.8±0.2
December 1956	10 months	3.7±0.4	1.4±0.2
November 1956	22 months	5.7±0.3	3.8±0.2
Cow bone			
October 1956	Foetal	144	8.6
October 1956	3 weeks	28.3	5.3
October 1956	4 weeks	43.4	5.1
October 1956	6 years	15.6	8.1
October 1956	13 years	18.7	3.8
August 1956	Old	6.3	3.3
August 1956	Old	8.4	6.9

I^{131} as an internal source

84. Measurements of I^{131} are of interest because of the selective concentration of iodine by the thyroid glands of man and animals. The normal human thyroid weighs 20-35 g and contains about 10 to 15 mg of stable iodine. All soft tissue has small amounts of stable iodine and blood plasma contains about 0.05 μg/cm^3.[75] The effective half-life of I^{131} in the body is very close to the radioactive half-life, 8 days.[67]

85. Since 1954, many laboratories have measured activities of I^{131} from fall-out in human and cattle thyroids.[76-80] The thyroid samples obtained from autopsies are counted with scintillation counters calibrated against I^{131} standards. In some cases the results are corrected using values from muscle measurements to eliminate the K^{40} and Cs^{137} contributions.

86. Apparently the cattle contamination is from two sources: inhalation and feeding on contaminated pastures. Results obtained by feeding cattle on fresh fodder or with barn fodder during the same periods suggest that 70 per cent of the I^{131} uptake is from intestinal absorption,[80] but there are other experiments that indicate both higher[81] (up to 95 per cent) and lower[77] percentage from this route of entry.

87. Results of measurements of the I^{131} content in cattle thyroids from various laboratories show a large spread of values. Neglecting high values from areas near test sites, average results for cattle from different geographical locations are comparable, and are of the order of 1 to 100 $\mu\mu$c/g thyroid for the period May 1955 to the end of 1956.[76,78] On account of the short half-life, I^{131} concentrations in thyroids vary with time as related to weapon tests.[79,80]

88. I^{131} activities in human thyroids are lower than in those of cattle from the same area and show less spread in the values. Considering only the I^{131} activities from a group of barn-fed cattle and correcting for different respiratory volumes, values similar to those of human thyroids are obtained.[80] This supports the idea that the human I^{131} intake is through inhalation. In some areas of the United States away from test sites, the I^{131} concentrations in human thyroids averaged about 4 $\mu\mu$c/g thyroid during May 1955.[80] The human thyroids measured were mostly from adults (more than 50 years old), but a few samples from persons of different ages

† A biological half-life of strontium of 11 years is used.[47]

suggested that the I^{131} activity increased slightly with age.[80] The human thyroid concentrations also vary with time according to weapon test periods. It is therefore difficult to estimate the integral thyroid dose over a period of time.

89. Considering the linear dimensions of the normal thyroid gland, it can be computed that the gamma contribution to the average thyroid dose is about 10 per cent of the beta contribution.[82] Integrating the data for the United States, excluding areas immediately adjacent to test sites, average doses of the order of 5 mrem/year are found in man for the years 1955 and 1956.[80] Dose from I^{131} in soft tissues is of the order of 10^{-4} times the thyroid dose.[D84] Therefore the average annual gonad dose in the United States for the years 1955 and 1956 was of the order of μ rem.

90. In areas near test sites, short-lived iodine isotopes will reach the thyroids. From the half-lives and average energies of these isotopes, the thyroid dose delivered can be computed as 4 times the dose from I^{131} if radioiodine is inhaled about 10 hours after the nuclear explosion,[83] but after 10 days the contribution is negligible.

VI. Estimation of doses from future fall-out

91. Data on present fall-out rates and accumulated deposits and the human burden of fission products allow the estimation of present dose rates. However, for evaluation of future genetic and somatic effects it is required to estimate the 30-year and 70-year doses. This estimation can of course be based on computations only of future fall-out rate and deposit and not on experimental data. It is possible, however, to make these computations using available data and certain assumptions which have at present little if any support in physical data. The results must therefore be considered only in connexion with these assumptions and necessarily cannot be any more valid than these.

92. Once the values for the future average world-wide fall-out rate and deposit have been calculated, the next step is to evaluate the doses received by human beings. This requires calculations based on factors, some of which are uncertain and others which cannot be generalized for the world's population, such as agricultural conditions and practices or living and dietary habits.

93. Owing to all these factors the evaluation of doses is rather uncertain. Furthermore, no indication, based on experiments, can be given as to the degree of uncertainty involved in the evaluations, but an attempt has been made to choose the more pessimistic of the possible alternative assumptions, and the over-all calculations may therefore overestimate the doses to be expected from future fall-out.

Estimation of fall-out rate and deposit in the future

94. A major part of the long-lived components of fall-out arises from the stratospheric reservoir, which is built up by "high yield explosions".[D6] It has been reported that about 10 per cent of the deposited Sr^{90} comes from tropospheric fall-out[9,13] in areas far from test sites (Sweden and United Kingdom). In the United States the contribution is estimated to be about 30 per cent,[12] which may be taken as representative for areas relatively close to test sites. Only a small error, therefore, is introduced in considering that all the Sr^{90} fall-out arises from the stratospheric reservoir. As Cs^{137} and Sr^{90} have approximately the same half-life and fission yield, and similar gaseous precursors in the fission chain, the following evaluation will be assumed to apply for both isotopes.

95. The material balance of Sr^{90} in the stratosphere-earth system can be described by the following general equations:

$$\frac{d\bar{Q}(t)}{dt} = n - \lambda\bar{Q}(t) - \bar{F}_r(t) \qquad (4)$$

$$\frac{d\bar{F}_d(t)}{dt} = \bar{F}_r(t) - \lambda\bar{F}_d(t) \qquad (5)$$

where:

n is the injection rate of Sr^{90} into the stratosphere per unit area (mc/km²·year). (n is as a convention assumed to be uniform for all the earth's surface. This assumption implies a relatively fast latitudinal stratospheric mixing.)

$\bar{Q}(t)$ is the Sr^{90} content of the stratosphere, expressed per unit area (mc/km²).

$\bar{F}_r(t)$ is the world-wide average fall-out rate of Sr^{90} per unit area (mc/km²·year).

$\bar{F}_d(t)$ is the world-wide average accumulated deposit of Sr^{90} per unit area (mc/km²).

λ is the disintegration constant of Sr^{90} (0.025/year).

96. These equations do not imply any particular relation between the stratospheric content and the fall-out rate, nor do they imply any specific function for the variation of n with time. The equations, therefore, cannot be fully resolved. At present, data on n are not available to the Committee. The computations will therefore be carried out for hypothetical cases of future values for n. Equation (5) implies that no leaching or weathering occurs.

97. Analysis of fall-out material has shown that Sr^{90} can remain in the stratosphere for many years before being deposited on the earth. The depletion mechanism of the stratospheric reservoir is not yet adequately known. It has been estimated from measurement of fall-out rate and stratospheric content that the annual Sr^{90} fall-out is about 12 per cent of the stratospheric content.[2] This annual fraction corresponds to a mean residence time of about 8 years, which is in agreement with a value of 10 ± 5 years derived from unpublished data.[37] The concept of a constant fractional removal per year of the stratospheric content is inconsistent with meteorological principle. However, nothing better can be offered at present. If the concept is to be used, a mean residence time of about 5 years appears to be the best value and a reasonable upper limit is about 10 years.[84] The latter value has been used in the calculations to follow, since it tends to yield results on the pessimistic side.

98. For the calculations it will be introduced as working hypothesis that the annual fraction does not change with time:

$$\bar{F}_r(t) = k\,\bar{Q}(t)$$

where $k = 0.1$/year. It can be seen that all the following equations for $\bar{F}_r(t)$ and $\bar{F}_d(t)$ that depend on the value of k will give higher results for lower values of k*.

99. As the radioactive material is in the form of microscopic particles of various sizes, it might be expected that the residence time of this material in the stratosphere will be a function of the size spectrum of the particles. This has importance especially in the event that no new material is introduced into the stratosphere, because the depletion would then continuously change the size distribution.

* Using $k = 0.2$/year in the following computations gives doses that are 0 to 40 per cent lower than those obtained using $k = 0.1$/year.

100. It is now possible to present a model in which equations (4) and (5) can be integrated. The hypotheses of the model are the following:

(*a*) All the Sr^{90} fall-out comes from the stratospheric reservoir;

(*b*) The fall-out rate is proportional to the stratospheric content;

(*c*) The Sr^{90} deposited on the earth is not acted upon by weathering effects or leaching:

(*d*) The injection rate of Sr^{90} into the stratosphere n will be constant in the future. Two hypothetical cases giving two different values of n will be discussed below.

101. The general solutions of equations (4) and (5), using equation (6), are:

$$\bar{F}_r(t) = \bar{F}_r(0)\, e^{-(k+\lambda)t} + \frac{kn}{k+\lambda}(1 - e^{-(k+\lambda)t}) \qquad (7)$$

$$\bar{F}_d(t) = \bar{F}_d(0)\, e^{-\lambda t} + \frac{\bar{F}_r(0)}{k}(e^{-\lambda t} - e^{-(k+\lambda)t}) + \frac{n}{\lambda}\left(\frac{k}{k+\lambda} + \frac{\lambda}{k+\lambda} e^{-(k+\lambda)t} - e^{-\lambda t}\right) \qquad (8)$$

$\bar{F}_r(0)$ and $\bar{F}_d(0)$ are the values

for the fall-out rate and accumulated deposit at the time $t = 0$, which in the following will be taken as the end of 1958.

Case 1: The tests stop at the end of 1958

102. This implies that $n = 0$ for any subsequent time. Using this relation, equations (7) and (8) will be:

$$\bar{F}_r(t) = \bar{F}_r(0)\ e^{-(k+\lambda)t} \qquad (9)$$

$$\bar{F}_d(t) = \bar{F}_d(0)\, e^{-\lambda t} + \frac{\bar{F}_r(0)}{k}(e^{-\lambda t} - e^{-(k+\lambda)t}) \qquad (10)$$

Equations (9) and (10) show that the fall-out rate decreases exponentially from the moment of interruption of tests, while the fall-out deposit increases, goes through a maximum at a time:

$$t_{max} = \frac{1}{k} \ln \frac{\bar{F}_r(0)\,(k+\lambda)}{(\bar{F}_d(0) + \bar{F}_r(0)/k)k\lambda} \qquad (11)$$

(about 13 years after tests stop) and then decreases, eventually with the half-life Sr^{90}.

Case 2: Tests continue

103. For the calculations of future fall-out rate and deposit two assumptions are used: (*a*) the rate of fall-out of Sr^{90} will remain in the future at the constant value observed for the last four years, or (*b*) the rate of injection of Sr^{90} into the stratosphere will remain in the future at a value equal to the mean value for the years 1954 to 1958 inclusive. If tests are stopped at any subsequent time T, then $\bar{F}_r(t)$ and $\bar{F}_d(t)$ would from that moment on, with either assumption, be determined by the equations:

$$\bar{F}_r(t) = \bar{F}_r(T)e^{-(k+\lambda)(t-T)} \qquad (12)$$

$$\bar{F}_d(t) = \bar{F}_d(T)e^{-\lambda(t-T)} + \frac{\bar{F}_r(T)}{k}(e^{-\lambda(t-T)} - e^{-(k+\lambda)(t-T)}) \qquad (13)$$

104. *Assumption* (a). In the model adopted, this assumption implies that Q will remain at an equilibrium value, which has been caused by large initial injections, followed by a constant injection rate that compensates for the stratospheric depletion. This might have been the situation during the last four years, as illustrated in figure 2. From equations (4) and (6) it follows that:

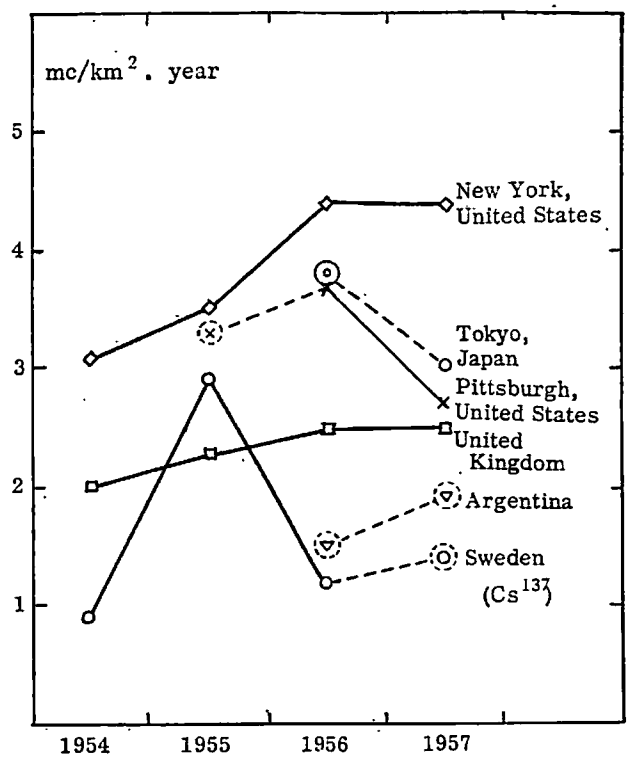

Figure 2. Fall-out rate of Sr^{90} determined by radiochemical analysis.[9,11,15,87,90,92] Values obtained by extrapolation of data for part of year are encircled.

$$n = \bar{F}_r(0)\,\frac{k+\lambda}{k} \qquad (14)$$

Using this relation, equations (7) and (8) will be:

$$\bar{F}_r(t) = \bar{F}_r(0) \qquad (15)$$

$$\bar{F}_d(t) = \bar{F}_d(0)e^{-\lambda t} + \frac{\bar{F}_r(0)}{\lambda}(1 - e^{-\lambda t}) \qquad (16)$$

If the tests go on indefinitely, $\bar{F}_d(t)$ will reach an equilibrium value of:

$$\bar{F}_d(\infty) = \frac{\bar{F}_r(0)}{\lambda} \qquad (17)$$

The 90 per cent equilibrium value will be reached in about 70 years.

105. *Assumption* (b). The period from the beginning of 1954 to the end of 1958 has been chosen[DI03] because the values of $\bar{F}_r(t)$ and $\bar{F}_d(t)$ were small before 1954 and the error introduced assuming both to be equal to zero would be small. The estimation of an average n for the period 1954 to 1958 inclusive implies in our model computing a constant n such that it would produce, in five years, the observed values of $\bar{F}_r(0)$ and $\bar{F}_d(0)$ at the end of 1958.

106. The total amount of Sr^{90} in the environment is $\bar{F}_d(t) + \bar{Q}(t) = \bar{F}_d(t) + \frac{\bar{F}_r(t)}{k}$. Therefore $\bar{n}$ (average for the period 1954 to 1958) is an $\bar{n}$ determined by:

$$\bar{F}_d(0) + \frac{\bar{F}_r(0)}{k} = \frac{\bar{n}}{\lambda}(1 - e^{-\lambda\tau}) \qquad (18)$$

where τ is 5 years, and $\bar{F}_r(0)$ and $\bar{F}_d(0)$ are the fall-out rate and deposit at the end of 1958. Under this assumption the solution of equations (7) and (8) is:

$$\bar{F}_r(t) = \bar{F}_r(0)e^{-(k+\lambda)t} + \frac{\bar{n}k}{k+\lambda}(1 - e^{-(k+\lambda)t}) \quad (19)$$

$$\bar{F}_d(t) = \bar{F}_d(0)e^{-\lambda t} + \frac{\bar{F}_r(0)}{k}(e^{-\lambda t} - e^{-(k+\lambda)t}) + \frac{\bar{n}}{\lambda}\left(\frac{k}{k+\lambda} + \frac{\lambda}{k+\lambda}e^{-(k+\lambda)t} - e^{-\lambda t}\right) \quad (20)$$

If tests go on indefinitely $\bar{F}_r(t)$ and $\bar{F}_d(t)$ will reach the equilibrium values:

$$\bar{F}_r(\infty) = \frac{\bar{n}k}{k+\lambda} \quad (21)$$

$$\bar{F}_d(\infty) = \frac{\bar{n}k}{\lambda(k+\lambda)} \quad (22)$$

The 90 per cent equilibrium values will be reached in about 15 and 100 years, respectively.

Values of $F_r(0)$ and $F_d(0)$

107. It is difficult from the available data to compute a world-wide fall-out rate and deposit, partly because large areas of the earth are insufficiently covered by the net-work of stations collecting data and partly because the different stations and laboratories do not all operate with comparable collection and evaluation methods. The estimation is especially difficult for the fall-out deposit, as many stations have only operated for less than two years.

108. The world-wide average of the fall-out rate of Sr^{90} was estimated from the latitude distribution curve, figure 1.[D18] It was assumed that the fall-out rates at the poles were zero. As measurements seem to indicate that the fall-out rate has been fairly constant over the last four years (see figure 2),[D104] the rate of 1.5 mc/km²·year obtained from the data from 1956 and 1957 has also been assumed valid for 1958.

109. The world-wide average of the accumulated fall-out deposit of Sr^{90} has been obtained from soil, pot and gummed film data.[5,9–13,20,22,23] The values obtained were extrapolated to the end of 1958 using the quoted value 1.5 mc/km²·year for the average fall-out rate, giving as an average about 5 mc/km² as the average accumulated deposit at the end of 1958.

110. Population weighted averages have been calculated using the same data as in paragraphs 108 and 109, and the latitudinal distribution of the world's population as obtained from a detailed population map.[85] At present, the maximum fall-out level occurs at the same latitude as the maximum population density and the population weighted averages for fall-out rate and deposit are at present higher than the area weighted averages by a factor of about 2. It is possible that this may change in the future and that in the event of cessation of tests it may approach unity. However, no allowance for this possible reduction has been made in the present calcula-

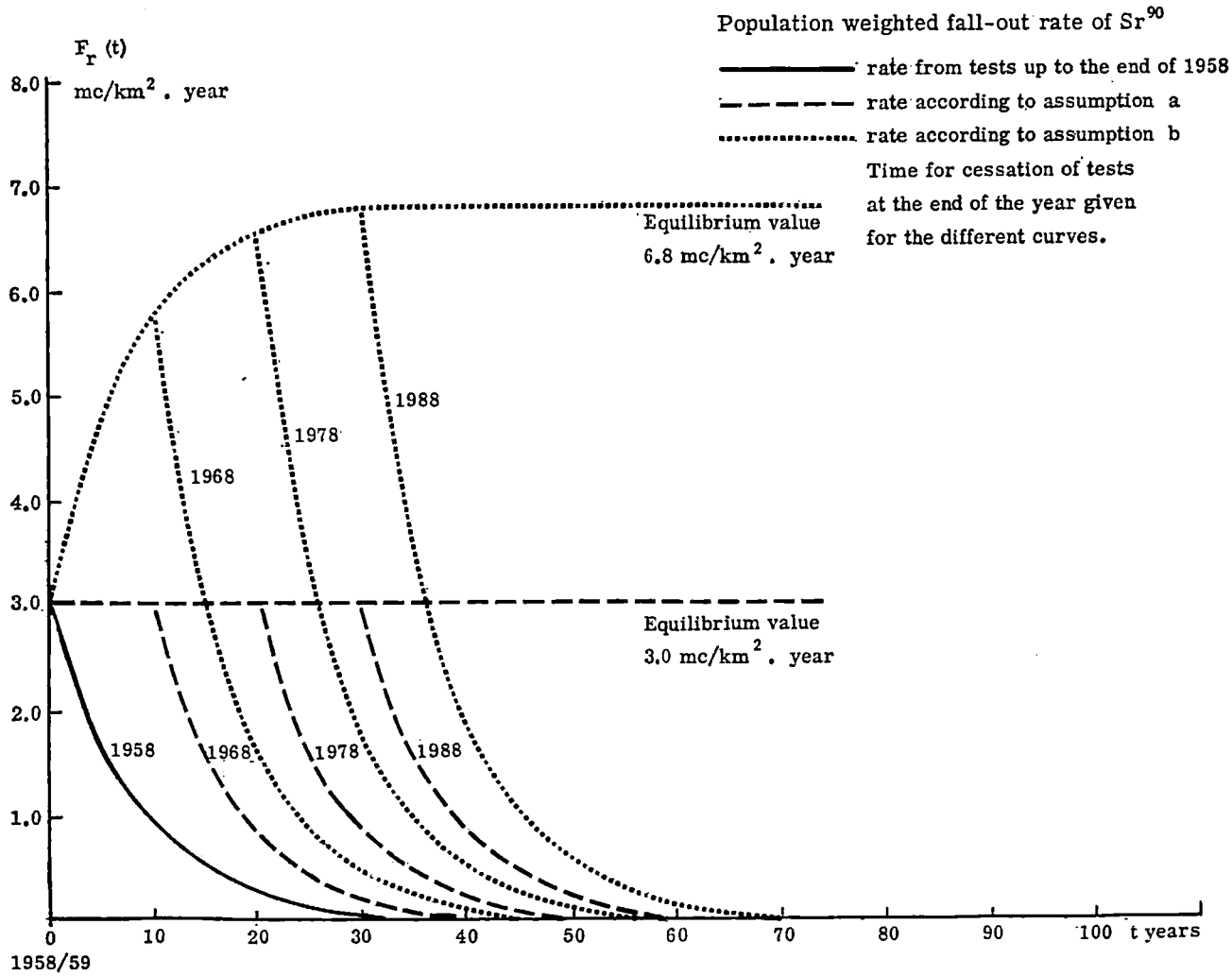

Figure 3

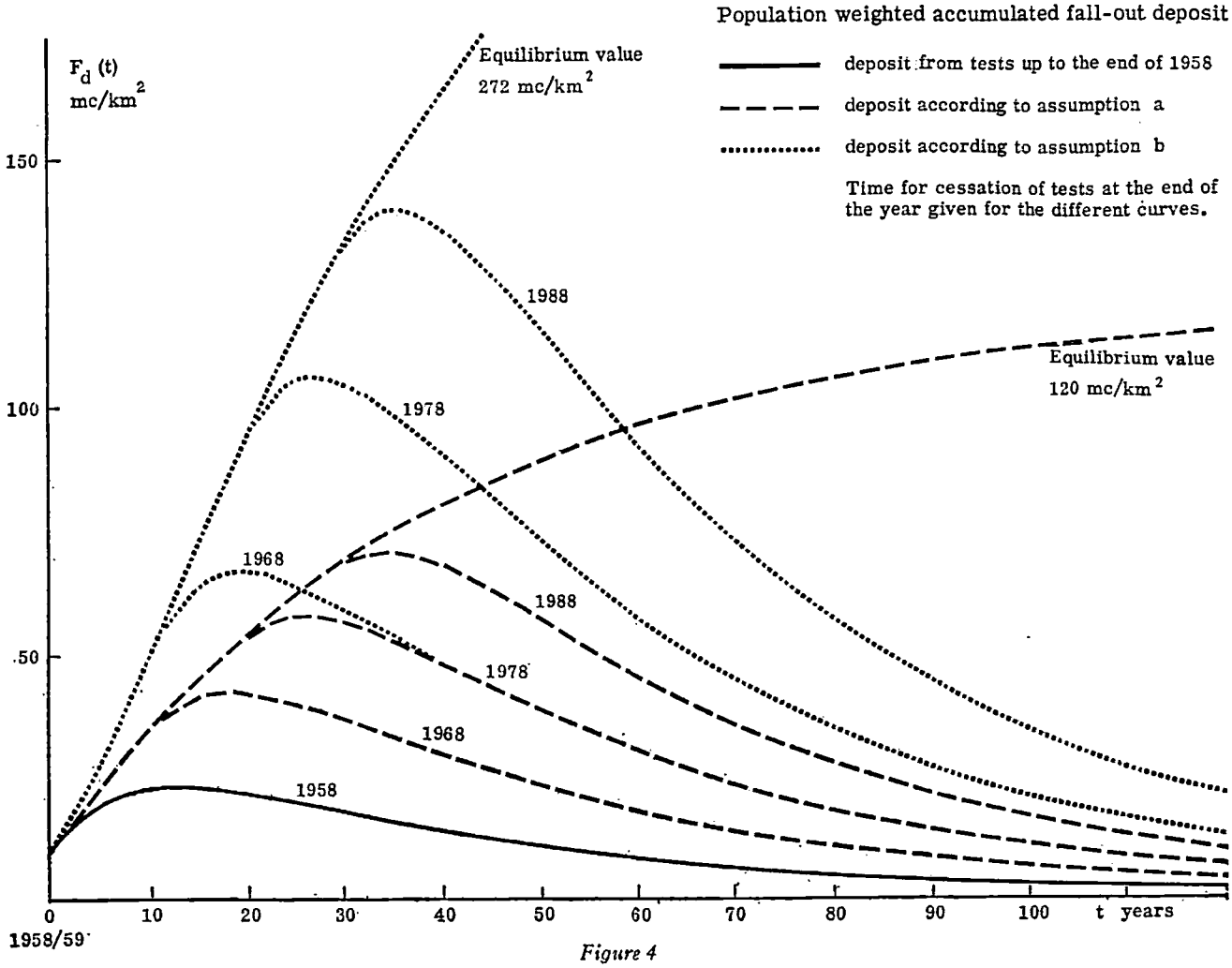

Figure 4

tions.** The population weighted values of the fall-out rate and of the accumulated deposit at the end of 1958 are accordingly taken as:

$$F_r(0) = 3 \text{ mc/km}^2 \cdot \text{year}$$

$$F_d(0) = 10 \text{ mc/km}^2$$

*Methods for dose estimations****

111. The equations derived above give the variation of the fall-out rate and deposit with time for the different cases studied (see figures 3 and 4). The computation of doses to human beings also requires information on the behaviour of Sr^{90} and Cs^{137} in the food-chain, and this introduces new uncertainties. The main information required is the extent to which the dose rate is correlated to fall-out rate and to fall-out deposit and the values of these correlation factors. At present the available information is insufficient and has to be complemented by some assumptions.

112. In the following paragraphs dose computations will be considered for:

(*a*) External irradiation of gonads caused by Cs^{137};

(*b*) Internal irradiation of gonads caused by Cs^{137};

(*c*) Internal irradiation of bone marrow caused by Sr^{90}.

In addition to the cases of (1) cessation of tests at the end of 1958 and (2) continuation of tests until equilibrium is reached, the doses for cases of (3) interruption of tests at different times in the future are also given as percentages of the equilibrium dose.

External irradiation of gonads caused by Cs^{137}

113. Equation (1)[D22] shows that the exposure rate from external irradiation is proportional to the accumulated fall-out deposit:

$$I = c \times \overline{E}_\gamma \times F_d^T(t) \qquad (1)$$

Taking into account a reduction factor c^1 to take care of shielding, leaching and weathering effects, the dose rate is given by:

$$\left(\frac{dD}{dt}\right)_e = c \times c^1 \times E_\gamma \times F_d^T(t) = g_e \times F_d^T(t) \qquad (23)$$

Here $c \approx 0.1 \frac{\text{mrad} \cdot \text{km}^2}{\text{year} \cdot \text{mc} \cdot \text{Mev}}$ and c^1 will be assumed to be 0.1.[D25] In the case of exposure from Cs^{137} the value to

** For population weighted average fall-out rate and accumulated deposit the symbols $F_r(t)$ and $F_d(t)$ are used (without bar). As $F_r(0)$ and $F_d(0)$ are a factor of 2 higher than $\overline{F}_r(0)$ and $\overline{F}_d(0)$, respectively, it can be seen from equations (7), (8), (14) and (18) that also $F_r(t)$ and $F_d(t)$ are a factor of 2 higher than $\overline{F}_r(t)$ and $\overline{F}_d(t)$.

*** For the dose estimations population weighted average fall-out rate and accumulated deposit $F_r(t)$ and $F_d(t)$ will be used.

be used for $\bar{E}\gamma$ is 0.92 × 0.89 × 0.661 Mev (92 per cent of the disintegrations give γ-rays of energy 0.661 Mev and of these γ-rays 11 per cent are converted.) The dose rate from deposited Cs^{137} is therefore:

$$\left(\frac{dD}{dt}\right)_e = g_e \times F_d(t) = 0.005 \times F_d(t) \text{ mrem/year} \quad (24)$$

Internal irradiation of gonads caused by Cs^{137}

114. The human burden of Cs^{137} at present depends primarily on the fall-out rate of Cs^{137},[D69] thus giving the dose rate:

$$\left(\frac{dD}{dt}\right)_i = g_i \times F_r(t) \quad (25)$$

Calculations from experimental data show that the average gonad dose rate amounts to about 1 mrem/year in the United Kingdom and the United States during 1956 and 1957.[D76] The observed fall-out rate of Sr^{90} in those countries was about 3 mc/km² during the same years (figure 2).[D104] Assuming the same fall-out rate for Cs^{137} as for Sr^{90} (probably an underestimate), the dose rate due to internal irradiation from Cs^{137} is 0.3 mrem/year for a fall-out rate of 1 mc/km². If in the future the dose rate is proportional to the fall-out rate, then:

$$\left(\frac{dD}{dt}\right)_i = g_i \times F_r(t) = 0.3 \times F_r(t) \quad (26)$$

Total irradiation of gonads caused by Cs^{137}

115. The total dose rate for the gonads from Cs^{137} is

$$\frac{dD}{dt} = g_e F_d(t) + g_i F_r(t) \quad (27)$$

The 30-year doses for the two assumed injection rates (assumptions *a* and *b*) and for the different cases considered for cessation of tests are therefore given by

$$D_{30} = \int_0^{30} \frac{dD}{dt} dt = g_e \int_0^{30} F_d(t)dt + g_i \int_0^{30} F_r(t)dt \quad (28)$$

The equations for $F_d(t)$ and $F_r(t)$ to be inserted in the different cases can be found elsewhere in annex D, identified by their numbers as given in table XII.

TABLE XII. EQUATIONS FOR USE IN FORMULAS (28), (34) AND (35)

	$F_d(t)$		$F_r(t)$	
	Assumpt. a	*Assumpt.* b	*Assumpt.* a	*Assumpt.* b
Tests stop end of 1958.....	(10)		(9)	
Tests stop end of 1968, T = 10	(16) and (13)	(20) and (13)	(15) and (12)	(19) and (12)
Tests stop end of 1978, T = 20	(16) and (13)	(20) and (13)	(15) and (12)	(19) and (12)
Tests stop end of 1988, T = 30	(16) and (13)	(20) and (13)	(15) and (12)	(19) and (12)
Tests continue.....	(16)	(20)	(15)	(19)

The 30-year doses become functions of the time for the start of integration, i.e., of the time of birth of the persons concerned. It can be shown that the maximum occurs for persons born at the end of 1958.† If tests continue, the maximum doses occur when equilibrium conditions are reached for fall-out rate and deposit. In order to compute the total of individuals genetically affected by a given series of tests, it is necessary to add up the D_{30} values for all population groups born in successive years. Because the doses are almost completely delivered over only a few decades for tests ceasing at the end of 1958, these sums of D_{30} values over all successive population groups are satisfactorily approximated for the present purpose by the maximum values of D_{30} in table XIII, if these are assumed to apply over a period of 30 years.

*Internal irradiation of bone marrow caused by Sr^{90}**

116. Any estimation of future levels of Sr^{90} in human bone is extremely difficult because it depends both on estimations of the Sr^{90} fall-out rate and deposit in the future and on estimations of how these levels will influence the concentration of Sr^{90} in bone. This last problem is particularly uncertain, as the uptake in the bone is very much dependent on the dietary habits and the food technology in a given region.[D50–D54] As it has been discussed in paragraphs 37 to 46, the uptake of Sr^{90} in different plants at different locations may be dependent on a number of factors, such as fall-out rate, accumulated deposit and the amount of available calcium in soil.

117. The following paragraphs provide calculations of the equilibrium diet-bone concentrations to be expected in humans subsisting on each of two foods: milk and rice. In actual practice, a population does not subsist entirely on either milk or rice, and these calculations should, therefore, be accepted as approximations based on conditions which would not in practice be realized.

118. The concentration of Sr^{90} in human bone in equilibrium with contaminated food can be estimated using formula (3) in paragraph 40 if milk is the main source of calcium in the diet:

$$C_M^B = DF_{(\text{milk} \to \text{bone})} \times C_M = DF_{(\text{milk} \to \text{bone})} \times (a_M(F_d + \tfrac{1}{2}f_d) + b_M f_d) \quad (29)$$

where C_M^B is the concentration of Sr^{90} in newly formed bone, $DF_{(\text{milk} \to \text{bone})}$ the discrimination factor from milk to bone and the rest of the symbols are as in paragraph 40.

119. It will be assumed that, in the future, the accumulated deposit, $F_d(t)$, will be the determining factor for the milk contamination.[D46] Using a value of a_M intermediate between those determined for Perry, N. Y.,[D41] and in the United Kingdom,[D43] and $DF_{(\text{milk} \to \text{bone})} = 0.5$ (table III),[D36] a simplified equation will be:

$$C_M^B \approx 0.15 \times F_d(t) \quad (30)$$

where C_M^B is given in strontium units when $F_d(t)$ is in mc/km².

† This becomes slightly incorrect when the cessation date is later than about 1978. Even for cessation in 1988, however, the approximation is good if the tropospheric contribution to the doses is added.

* The bone marrow dose from external and internal Cs^{137} can be calculated by integration of equation (27) over 70 years. The dose contribution is of the order of 10 per cent or less than that from Sr^{90} in bone and has accordingly been neglected in table XIII.

120. In the cases where rice is the main source of Sr^{90} in the diet, a formula has been derived to cover the rather unusual method of farming this grain in Japan, where most of the plant material from earlier crops is ploughed down in a homogeneously cultivated soil.[34]

$$C_R^B = DF_{(soil \rightarrow rice)} \times DF_{(rice \rightarrow bone)} \times \frac{1}{A} \times F_d(t) \quad (31)$$

C_R^B is the concentration of Sr^{90} in newly formed bone. $DF_{(soil \rightarrow rice)}$ and $DF_{(rice \rightarrow bone)}$, the discrimination factors from soil to rice and from rice to bone, are taken as 0.5 and 0.17 respectively[D36,D47]. A is the amount of available calcium in the soil, approximately 95×10^6 g/km² (with outer limits approximately 30×10^6 and 230×10^6 g/km²).[34] The formula will in this case be:

$$C_R^B \approx 0.9 \times F_d(t) \quad (32)$$

where C_R^B is given in strontium units when F_d is in mc/km².

121. It is evident that the equations (30) and (32) for concentrations of Sr^{90} in bone are uncertain. The neglect of foliar retention and of sources of Sr^{90} other than milk tend to give bone concentrations that are too low, especially in the immediate future. It must be emphasized that the bone concentrations are calculated only for newly formed bone.[D118]

122. The mean bone marrow dose is assumed to be 1 mrem/year for a bone concentration of 1 strontium unit.[D64] Therefore the dose rate in bone from Sr^{90} will be:

$$\frac{dD}{dt} = C^B \quad (33)$$

where C^B is the concentration of Sr^{90} in newly formed bone, as given by equations (30) and (32) for the two diets considered. The 70-year doses for the two assumed injection rates (assumptions *a* and *b*), and for the different cases considered for cessation of tests are therefore obtained by integration over 70 years of equation (33), giving, for the hypothetic milk diet:

$$(D_{70})_M = 0.15 \int_0^{70} F_d(t)\, dt \quad (34)$$

and for the hypothetical rice diet:

$$(D_{70})_R = 0.9 \int_0^{70} F_d(t)\, dt \quad (35)$$

The equations for $F_d(t)$ to be inserted in the different cases can be found elsewhere in annex D, identified by their numbers as given in table XII. The doses are calculated for persons born at the end of 1958, which give approximately the maximum 70-year doses. If tests continue, however, the maximum doses occur when equilibrium conditions are reached for accumulated deposit, and have accordingly been calculated for that case.

123. To use the equations (30) and (32) in these computations implies the assumption that the whole skeleton has, at any time, the same concentration of Sr^{90} as bone which is newly formed at that time. The Committee is aware that this assumption is not consistent with the rather long biological half-lives of calcium and strontium. It is, however, a satisfactory approximation for the purpose of the present calculations, which it greatly simplifies. Moreover, this extreme assumption tends to over-estimate the average 70-year dose, and so the calculations may be taken as an upper limit for those population cohorts receiving the maximum 70-year exposure.

Estimated doses

124. Table XIII shows the results of the computations for the different cases. The numbers should only be considered in connexion with all the assumptions and uncertain factors discussed in the preceding and following paragraphs.

125. For the estimations of future fall-out rate and accumulated deposit the regional values can be expected to differ by a factor of about ⅕ to 2 depending mainly upon latitude.[D18] In some areas of the world the tropospheric fall-out may tend to raise the upper limit of this range, especially in the vicinity of test sites.

126. The uncertainties in the calculations of doses, based on the estimated fall-out levels, may be considerable, but are difficult to evaluate because of insufficient experimental data. It seems, however, that the experimental data indicate an uncertainty in the *per capita* mean marrow doses of a factor of about 3 merely because of regional variations in the conversion factors from fall-out deposit to bone concentration of Sr^{90}.[D119-120]

VII. Calculation of biological effects**

127. The frequency of certain possible consequences of radiation has been estimated on the following basis:

Leukemia, assuming a linear dose response relationship and no threshold

128. In this case, the number of individuals affected annually (R_1) is calculated from the appropriate 70-year mean marrow dose (D_{70}), the dose effect constant (K_1) for leukemia as derived in annex G, paragraph 50, and the assumed world population (P), and dividing by 70 to give a mean annual rate. Thus:

$$R_1 = \frac{D_{70} \times K_1 \times P}{70} \quad (36)$$

K_1 is here calculated on the assumption that a leukemia incidence of 1.5 cases per million per year per rem continues after each element of radiation exposure for the remaining life of the individual, or for an average period of 35 years in a population living to age 70. K_1 has thus a value of 52 cases per million per rem.

(*a*) In estimating on this basis leukemia ascribable to natural radiation, D_{70} is 7 rem (annex C, table XXV) and R_1 is calculated for $P = 3 \times 10^9$ and 5×10^9, giving values of R_1 of 15,800 and 26,200. (The natural occurrence of leukemia is calculated on a basis of 50 deaths per million per year.)

(*b*) Leukemia ascribable to fall-out from weapon tests, if such tests stop in 1958, is calculated with $P = 3 \times 10^9$ and with values of 0.16 and 0.96 for D_{70}. These are estimates for milk and for rice diets (table XIII), and would correspond to incidences of 360 and 2,160 cases per year. Because most of the dose is actually delivered during a few decades, the total of induced cases would about equal $70R_1$ and so would be 25,200 to 151,000.

(*c*) Leukemia attributable to fall-out in equilibrium conditions reached after prolonged testing is calculated for $P = 5 \times 10^9$. The values of D_{70} (table XIII) range from 1.3 rem under assumption *a* and with a milk diet, to 17 rem under assumption *b* and with a rice diet, giving incidences of 4,880 and 63,800 cases per year.

** For the purpose of table II, chapter VII, of the report the figures calculated in the following paragraphs have been rounded off.

TABLE XIII. ESTIMATED DOSES FROM STRATOSPHERIC FALL-OUT[a] (computed from population weighted world-wide average values of stratospheric fall-out rate and deposit)[b]

	Genetically significant dose: Maximum for any 30-year period (rem)		Per capita *mean marrow dose: Maximum for any 70-year period (rem)*			
			Estimates for countries deriving most of dietary calcium from milk[c]		*Estimates for countries deriving most of dietary calcium from rice*[c]	
Weapon tests cease at end of 1958	0.010		0.16		0.96	
	Assump. a[d]	*Assump. b*[d]	*Assump. a*[d]	*Assump. b*[d]	*Assump. a*[d]	*Assump. b*[d]
Weapon tests continue until equilibrium is reached in about a hundred years	0.045	0.10	1.3	2.8	7.5	17

	Estimated percentages of the maximum doses for continued weapon tests			
	Assump. a[d]	*Assump. b*[d]	*Assump. a*[d]	*Assump. b*[d]
Weapon tests cease:				
1958	22	10	13	6
1968	45	33	24	16
1978	63	55	34	26
1988	72	62	42	35
Weapon tests continue	100	100	100	100

[a] The methods used for calculation of these doses are given in paragraphs 91 to 123.

[b] Regional values may differ by a factor of 1/5 to 2 from the estimated population weighted world-wide average values because of the latitudinal variation of fall-out rate and deposit. In some areas of the world the tropospheric fall-out may tend to raise the upper limit of this range, especially in the vicinity of test sites.

[c] The extent to which these estimates apply to populations of different dietary habits and to those living in areas of differing soil conditions is discussed in paragraphs 116–121.

[d] Assumption *a* is that the injection rate is such as to maintain a constant fall-out rate of Sr^{90} and Cs^{137}, whereas assumption *b* is that weapon tests equivalent in release and stratospheric injection of fission products to the whole sequence of weapon tests from the beginning of 1954 to the end of 1958 will be repeated at constant rate. This second assumption will give an equilibrium value for the fall-out rate and deposit approximately a factor of 2 higher than that calculated by using the first assumption.

Estimates for milk diet with assumption *b* and for rice diet with assumption *a* are 10,500 and 28,200 cases per year.

Leukemia, assuming a threshold of 400 rem

129. On this hypothesis, cases of leukemia might result if the 70-year dose exceeded 400 r at any point in the marrow. The maximum dose in marrow might, in a small cavity, equal that in surrounding bone; and it is possible that such bone might, owing to irregularities in mineralization, receive a dose of up to twice the mean bone dose, which in turn is estimated to be about 2.5 times the mean marrow dose (taking a mean bone dose of 2.5 mrem per year per strontium unit*** and a mean marrow dose of 1 mrem per year per strontium unit). The maximum marrow dose might thus equal 5 times the mean marrow dose.

(*a*) With natural radiation, a threshold of 400 rem will only be exceeded in an individual receiving 400/7, or 57 times the normal D_{70} of 7 rem.

(*b*) With fall-out from tests ending in 1958, the mean marrow doses of 0.16 and 0.96 on milk and rice diets correspond to maximum marrow doses of 0.80 and 4.8. The threshold would thus be exceeded by individuals receiving 400/0.8 and 400/4.8, or 500 and 83 times, the average values of D_{70}.

(*c*) Under equilibrium conditions of fall-out after prolonged continuation of tests, the mean 70-year marrow doses would range from 1.3 to 17 rem, and the corresponding maximum marrow doses would be 6.5 and 85 rem. A threshold of 400 rem would thus be exceeded by individuals receiving 62 times the average value for milk diet with assumption *a*, and 4.7 times this value for rice diet with assumption *b*.

*** A mean osteocyte dose of 2.5 mrem per year per strontium unit has also been used for the purpose of the calculations of the numbers given in note to table II, chapter VII.

This report affords only very incomplete evidence as to the likely variation of individual marrow doses from the mean values, and no estimate is given of the way in which the risk of leukemia might increase once a threshold dose was exceeded. These results, on the hypothesis that a 400 rem threshold exists, therefore give only a general indication of the relative hazards in different circumstances.

Major genetic-defects

130. For the purpose of these calculations it is assumed that, by the time any mutations currently occurring came to be expressed as damage in the population, the world population would have become stabilized at $P = 5 \times 10^9$, half of whom were below the mean age of reproduction.

The total number of births would be $5 \times 10^9/70$ and a part (K_g) of these would be affected by major genetic defects (annex H, table XI), the value of K_g being assumed from present experience to lie between 1 and 4 per cent of all births. The normal occurrence of such defects would thus be from 715,000 to 2,860,000 per year.

The total number of births affected by a 30-year gonad dose D_{30} is given by

$$\frac{D_{30}}{\overline{D}_2} \times K_g \times \frac{P}{2} \qquad (37)$$

where $\overline{D}_2$ is the representative doubling dose and is assumed to lie in the range 10 to 100 rem. Under equilibrium conditions, the evaluated rate of such births would be

$$\frac{D_{30}}{\overline{D}_2} \times K_g \times \frac{P}{2 \times 30} \qquad (38)$$

(a) *Radiation from natural sources*

For $D_{30} = 3$ rem (annex B, table XXV) the rate of

affected births is $\frac{3}{(10 \text{ to } 100)} \times \frac{(1 \text{ to } 4)}{100} \times \frac{2.5 \times 10^9}{30}$
= 25,000 to 1,000,000 per year.

(b) *Fall-out, tests stopping in 1958*

The total gonad dose is about equal to the maximum 30-year dose of 0.01 rem (table XIII) so that the total number of affected births is $\frac{0.01}{(10 \text{ to } 100)} \times \frac{(1 \text{ to } 4)}{100} \times 2.5 \times 10^9$ = 2,500 to 100,000 births.

No rate can appropriately be given since these births will occur over a period prolonged beyond the 30-year interval over which the dose is integrated.

(c) *Fall-out, tests continuing for a prolonged period*

The values of D_{30} are 0.06 rem and 0.12 rem on assumption *a* and *b* (table XIII)†, giving rates of

$$\frac{(0.06 \text{ or } 0.12)}{(10 \text{ to } 100)} \times \frac{(1 \text{ to } 4)}{100} \times \frac{2.5 \times 10^9}{30}$$

Rates are thus 500 to 20,000 on assumption *a* and 1000 to 40,000 on assumption *b*. Rates can here be given since equilibrium conditions are postulated.

VIII. Note on information document

131. A document (A/AC.82/INF.3) entitled: "An approach to a general method of computing doses and effects from fall-out" was prepared by the Secretariat of the United Nations in collaboration with a group of experts of the Committee, as a working paper. It was completed just before the Committee's last session (9-14 June, 1958). The Committee has not had sufficient time to study and eventually to accept this work which was considered to be of substantial scientific interest; it has decided to make this paper available because it will be useful to scientists engaged in calculations of gonad or bone marrow doses and their biological effects.[97]

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Tables containing data on fall-out from reports submitted to the United Nations Scientific Committee on the Effects of Atomic Radiation

Table XIV. External irradiation due to fall-out

Country	*Argentina*	*Denmark*	*France*	*Japan*	*Mexico*	*Netherlands*	*Norway*	*Sweden*	*United States*
Sampling method	Stainless steel pot	Plate	Funnel combined with gummed film	Polyethylene sheet and porcelain tray	Gummed film	Stainless steel pot	Stainless steel pot	Funnel	Gummed film
Sampling period	1 month	24 hours (if more than 0.5 mm precipitation is collected)	1 month or after each precipitation	Dust: 24 hrs., water after each precipitation	2 to 3 days	2 days	24 hours	4 to 30 days or during precipitation	24 hours
Period of measurement	Jan. to Sept. 1957	Jan. to Dec. 1956	April 1955 to July 1957	May 1954 to June 1957	May 1956 to Oct. 1957	Nov. 1955 to Oct. 1957	Oct. 1956 to Sept. 1957	April 1953 to June 1957	Oct. 1952 to June 1957
Total accumulated activity from fall-out (mc/km^2)[a]	41[b]	60	50[b]		150[b]		94–377	70	
"Infinite plane" exposure during a 30-year period, from the total fall-out during the period of measurement (mrad).				123[c]	9 (4–13)[d]	24[c]		25	55[c] (20–180)
Factor of reduction due to weathering				3		2			
Factor of reduction due to shielding by buildings				1		3			
Total reduction factor				3	7	6			

[a] Activity at the end of the period of measurement, comprising local tropospheric and stratospheric fall-out deposited during that period.
[b] Extrapolated to 1 January 1958.
[c] Dose for infinite time. This dose is only slightly different from the 30-year dose.
[d] From fall-out during the period March–October 1957.

TABLE XV. Sr^{90} FALL-OUT ON THE GROUND

Country	*Argentine*	*Belgium*	*France*	*Japan*	*Mexico*	*Netherlands*	*Norway*	*Union of South Africa*	*Union of Soviet Socialist Republics*	*United Arab Republic (Egypt)*	*United Kingdom*	*United States*
Sampling method.....	Stainless steel pot	Aluminium pot	Funnel combined with gummed film	Polyethylene sheet and porcelain tray	Gummed film and pot	Stainless steel pot	Stainless steel pot	Porcelain pot	Gauze	Gummed film	Funnel	(*a*) Gummed paper (*b*) Stainless steel pot (*c*) Galvanized [illegible]
Sampling period.....	1 month	24 hours	1 month, or after each precipitation	Dust: 24 hrs., water after each precipitation	2 to 3 days	2 days	24 hours	24 hours	24 hours	24 hours	1 month	(*a*) 24 hours (*b*) 1 wk.–1 mo (*c*) 3 to 7 days
Period of measurement..	Jan.–Sept. 1957	Apr.–Nov. 1957	Apr. 1955–July 1957	(*a*) May 1954–Aug. 1956 (*b*) Oct. 1956–June 1957	Mar.–Oct. 1957	(*a*) July 1955–Nov. 1956 (*b*) Dec. 1956–Nov. 1957	Mar.1956–June 1957	Jan.–Apr. 1956	(*a*) Up to end 1955 (*b*) July–Sept. 1957	Mar.–Dec. 1957	May 1954–Apr. 1957	(*a*) Oct. 1951–June 1957 (*b*) Feb. 1954–Sept. 1957 (*c*) Mar. 1955–Nov. 1957
Method of determination of Sr^{90}.....	Rad.chem. analysis	Rad.chem. analysis	Calculation[a]	(*a*) Calculation[a] (*b*) Rad.chem. analysis	Calculation[a]	(*a*) Calculation[a] (*b*) Radiochem. analysis	Calculation[a]	Rad.chem. analysis	Rad.chem. analysis of pooled samples	Rad.chem. analysis of pooled samples	Rad.chem. analysis	(*a*) Calculation[a] (improved) (*b*) and (*c*) Rad.chem. analysis
Accumulated deposit of Sr^{90} during the period of measurement (mc/km²).....	1.4	1.5	2.0	8.0[b]	0.6 (0.3–0.9)	Approx. 5.3	2.4	0.28	(*a*)1.6 (0.8–3.2)		7.5[c]	(*a*) 8.8(4.2–21) (*b*) 15[d] (*c*) 9.0[e]
Fall-out rate of Sr^{90} (mc/km²·year).....			1955: 0.6 1956: 0.7	1954: 1.0 1955: 0.7 1956: 3.8		(*a*) Approx. 2.3 (*b*) 2.3	Sept. 1956–Aug. 1957: 0.9		(*b*) 2.8 (2.2–4.3)	1.4	1954: 2.0 1955: 2.3 1956: 2.4[f]	1957 3.9[g] (1.9–6.2)

[a] Using Hunter and Ballou curves [8].
[b] Assumed a deposit of 0.4 mc/km² prior to May 1954.
[c] Assumed a deposit of 0.7 mc/km² prior to May 1954.
[d] New York City.
[e] Pittsburgh.
[f] Mean value from 4 funnel stations.
[g] Mean value from 8 pot stations.

TABLE XVI. MISCELLANEOUS DATA ON Sr^{90}

Country	Argentina	Brazil	Canada	Japan	Mexico	Norway	Sweden	Union of Soviet Socialist Republics	United Kingdom	United States
Sr^{90} in air at ground level (10^{-15} c/l)				Nov. 1955 to Nov. 1956: 53 (28–106)[a]				Mar. to Dec. 1955: 60–140 Sept.–Nov. 1957: 6.3–100	April 1952 to Jan. 1956: 4[a]	1953: 6.4 (3.0–11.2) 1954: 20 (1.0–60) 1955: 41 (3.6–120) June to Aug. 1956: 75
Sr^{90} in soil (mc/km^2)				1957: 3.6 (2.5–6.3)		1956: 4.6 (4.5, 4.6)	Summer 1956: 1.2[b] (0.6–2.0)	Feb. to July 1957: 6.0 (3.0–12)	March 1955: 1.7(0.5–2.9) July 1956: 4.7 (1.9–10)	1953: 1.5 (0.4–24)[c] 1955: 4.9 (0.8–7.5)[c] 1956: 6.9 (2.9–12)[c]
Sr^{90} in drinking water (10^{-14} c/l)				1957: 200		1957: 35 (15–55)				1954: 6.1 (4.5–9.0) 1955: 10.1 (4.9–33) 1956: 15.4 (1.4–26) 1957: 17.6 (0.7–27.2)
Sr^{90} in milk ($\mu\mu c/gCa$)	Apr. to June 1957: 3.5 (3.1, 3.9)	First months 1957: 2.7±0.3	1956: 5.0 (1.5–11.6) 1957: 6.2 (2.5–19.8)	1956: 2.4 (2, 1, 2.7) 1957: 2.9	Oct. to Dec. 1956: 1.2(0.5–1.5) Oct. to Dec. 1957: 3.0(2.5–3.5)	1957: 7.9[d] (4.5–15.5)		July 1956 to June 1957: 4.9 (2.2–8.0)	1955: 3.9 (1.8–6.4) 1956: 5.4 (2.9–10.3)	1954: 1.3 (0.5–2.3) 1955: 3.2 (0.3–3.10) 1956: 5.0 (1.3–17) 1957: 8.0 (1.9–33)
Sr^{90} in plants ($\mu\mu c/gCa$)				1956: Vegetables: 9.4 (1.1–23) White rice: 49 (36, 62) Brown rice: 154 (81–250) Rice bran and chaff: 450 (390–540) 1957: Brown wheat: 162 (153, 170) Wheat flour: 53				Cereals, 1956: 69 (28–140)	Grass 1955: 34 (5.5–53)[e] 1956: 30 (11–77)[e] 516(91–2100)[f]	Hay: 1954: 1.3 (0.5–2.3) 1955: 3.2 (0.3–10) 1956: 5.1 (1.3–17) 1957: 8.0 (1.9–33)
Sr^{90} in animal skeleton ($\mu\mu$ c/g Ca)			Cows, 1956: 5.2 (2.2–8.6)	Deer horn, grown 1954: 4.4 (1.6–9.9) 1955: 4.7 (1.0–11.7) 1956: 2.6 Fish, 1956 to 1957: Freshwater: 3.4 (0.4–11.4) Marine: 0.29 (0.19, 0.38)		Sheep, 1956: 24 (10–77)			Sheep 1955: 11.0 (8.0–13.9)[g] 52(5.7–183)[h] 1956: 13.0 (7.8–15.6)[g] 48(24–160)[h]	Cows and Sheep 1954: 3.3 (1.7–7.0) 1955: 7.8 (0.51–24)

[a] Calculated from total β-activity measurements.
[b] Preliminary data, probably too low because of the leaching method used (1M ammonium acetate).
[c] Sampled in October each year.
[d] In units of $\mu\mu c/l$.
[e] Grown on normal soil.
[f] Grown on acid hill soil.
[g] Lowland sheep.
[h] Highland sheep.

TABLE XVII. Sr^{90} IN HUMAN SKELETON
($\mu\mu c/gCa$)

Country	*Canada*	*Japan*	*Norway*[a]	*Union of Soviet Socialist Republics*	*United Kingdom*		*United States*
Period of measurement....	June 1956 to June 1957	Dec. 1956 to May 1957	Oct. 1956 to Dec. 1957	Second half 1957	Oct. 1955 to Dec. 1956	Jan. to June 1957	Dec. 1955 to July 1956
Age group							
Stillborn to 1 month.....	0.7 (0–1.1)	4.6 (4.1–4.6)	0.5		0.44 (0.15–0.8)	0.54 (0.4–0.7)	0.57 (0.45, 0.70)
1 month to 1 year.....	1.6 (1.4, 1.8)		0.8 (0–1.3)		0.70 (0.15–1.3)	1.5 (0.9–2.4)	0.83 (0.71–0.97)
1 year to 5 years.....	2.1 (0.1–3.8)		0.7 (0.2–1.1)	2.3 (1.6–3.2)[b]	0.85 (0.54–1.45)	1.3 (0.4, 2.2)	0.51 (0.10–1.7)
5 years to 20 years.....	0.1	0.73 (0.2–1.25)	0.4 (0.3–0.5)		0.26 (0.15–0.53)	0.39 (0.3–0.5)	0.47 (0.13–1.4)
More than 20 years.....	0.4 (0.1–0.6)	0.41 (0.04–1.75)	0.3 (0–0.7)		0.11 (0.06–0.2)		0.04 (0.02–0.11)

[a] Preliminary data, determined without using low-level counter. [b] Age 0 to 5 years.

TABLE XVIII. Cs^{137} FALL-OUT ON THE GROUND
(Determined by radiochemical analysis)

Country	*Japan*	*Sweden*	*United Kingdom*
Sampling method.....	(*a*) Precipitation collection (*b*) Soil	Funnel	Funnel
Sampling period.....	(*a*) 40 to 83 days	4 to 30 days or during precipitation	3 months
Period of measurement.....	(*a*) March to June 1957 (*b*) Aug. 1957	April 1953 to June 1957	Jan. 1956 to March 1957
Accumulated deposit of Cs^{137} during the period of measurement (mc/km^2).....	(*b*) 6.5	6.0	5.3 (3.8–6.7)
Fall-out rate of Cs^{137} ($mc/km^2 \cdot year$).....	(*a*) 2.3	July 1955 to June 1957: 1.3	

TABLE XIX. Cs^{137} IN FOODSTUFFS AND THE HUMAN BODY
(In units of $\mu\mu cCs^{137}/gK$)

Country	*Japan*	*Mexico*	*Norway*	*Sweden*	*United Kingdom*	*United States*
Period of measurement.....	1956 to 1957	Dec. 1956	1957	1956	June 1956 to July 1957	1956
Milk.....	81 (44–140)	40[a] (20, 60)	33[a] (4.0–107)	60[a]		25 (4–96)
Vegetables and fruit.....	6.4 (3.3–11)					13 (3–38)
Cereals and rice.....	48 (31–65)					20 (3–32)
Human body.....	30–60				34 (20–44)	30–70
Human urine.....	34 (9–78)					11 (7.2–14)

[a] In units of $\mu\mu cCs^{137}/l$.

TABLE XX. MISCELLANEOUS DATA ON FALL-OUT

Country	*Belgium*	*Brazil*	*Denmark*	*France*	*India*	*Italy*	*Japan*	*Netherlands*	*Norway*	*Sweden*	*United Arab Republic (Egypt)*	*United Kingdom*
Period of measurement of air concentrations of fission products.....	1957	May to July 1956	1956	1957	Feb. to Aug. 1956	Nov. 1956 to Jan. 1958	a) 1955 b) 1956 c) 1957	May 1956 to Dec. 1957	Mar. 1956 to Oct. 1957			April 1952 to Jan. 1956
Maximum concentration of fission products in air at ground level (10^{-16}c/l).....	14.8[a]		21.9[b]	87[b]	17.9[b]	33.2[a]	a) 14.7[a] b) 177.3[a] c) 153.6[a]	120[b]	18[b]			113[a]
Mean concentration of fission products in air at ground level (10^{-16}cll)	7.5	0.5	2.8	10	5.6	12.6	a) 5.9 b) 37.1 c) 54.1	9	7			2.3
Content of I^{131} in thyroids of cattle ($\mu\mu$c/g).....										Sept. 1956 100–800	May to Sept. 1956 11 (0–129) Oct. 1956 344 (3–1290)	
I_{131} in milk ($\mu\mu$c/l).....									1957 82 (0–1350)			

[a] Average over 1 month. [b] Average over 24 hours.

Annex E
METHODS OF MEASUREMENT

TABLE OF CONTENTS

I. INTRODUCTION

1. The ultimate purpose of radiological measurements of concern to the Committee is the estimation of tissue dose from natural sources, man-made sources and environmental contamination. In some cases, however, measurements of radioactivity are also of primary concern. It is emphasized that new and improved methods are constantly being developed.

2. It is customary to classify measurements of this nature into categories relating to the method used, i.e., direct or indirect. Direct exposure rate measurements are those made with ionization chambers or instruments calibrated in terms of air ionization. Indirect methods are those where exposure rate is calculated from activity measurement. The rates of exposure from medical and industrial practice and from terrestrial and cosmic radiation are sufficiently high to allow direct measurement. Exposure rates from other sources are low and the dose rate must usually be estimated indirectly by activity measurement and subsequent calculation.

Direct measurements

3. Routine direct determination of external exposures usually involves the measurement of gas ionization, as the relationship between energy absorption and ionization is relatively independent of energy. Any ionization chamber with an air equivalent wall may be used for the measurement, but it must be standardized periodically against a free air chamber.[1]

4. Scintillation counters, films and geiger counters can be used for rough estimation of exposure or exposure rate, but they can give erroneous results in mixed radiation fields. They can be valuable, however, if the composition of the field is known and they have been calibrated under similar conditions.

Indirect measurements

5. The indirect determination of exposures from radioactive sources, such as deposited fall-out or radioisotopes in the body, is more complex. It involves consideration of methods of sampling, radiochemistry and activity measurement. Methods for these are outlined in the following sections. The necessary dose computations are described in annexes B, C, and D.

II. SAMPLING

6. The determination of activity in the atmosphere, fall-out deposit, soil, foodstuff and human tissue requires the collection of samples representative of a given geographic region. Although this is difficult from a technical and statistical viewpoint, there are recognized methods.[2,3] It is recommended that the sampling of the environment and the biological materials be co-ordinated.

7. Radioactive material may be present in the atmosphere in gaseous or particulate form, each requiring its own sampling method. For measurement of radioactive gases, the sample must be obtained by collecting a measured volume of air in a suitable container[4–7] or by drawing a measured volume of air through an activated charcoal trap.[4,5,8] Both filters[4,5,9–14] and electrostatic precipitators are suitable for collection of airborne particulates.[5,11] These methods may also be used for very rough estimates of gaseous activities having solid daughters.[15,16] Deposited fall-out activity may be collected periodically by a high-walled pot[12–14,17–21] or high-walled funnel,[22–24] or the accumulated deposit may be obtained from soil samples.[25,26,D14]

8. It is not possible at present to state the absolute efficiency of any device for the collection of fall-out deposition. The high-walled pot is recommended as an arbitrary basis of comparison for other methods.

9. Samples of foodstuff should represent the regional diet, and should be selected with reference to the isotope of interest. Although it is advisable to take samples frequently, it is more economical to analyse a composite representing one or more months' collection.

10. The *in vivo* measurement of radioactive strontium or radium by whole body spectrometry is inadequate at present. Therefore samples of bone are required for estimation of the skeletal burden in man. Specifications for sampling have been given.[25,D66]

III. RADIOCHEMISTRY AND ACTIVITY MEASUREMENT

11. Radon may be measured by alpha counting in an ionization chamber[11,27,28] or scintillation counter.[29,30] The techniques suitable for air samples are also adequate for samples of exhaled breath for evaluation of

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.

the radium body burden. Standards may be prepared from commercially available radium solutions.[31,32]

12. The determination of strontium activity in the various materials described above involves preparation of the sample, separation of strontium and measurement of the activity.

13. The preparation depends on the type of sample: (*a*) soil from which strontium is removed satisfactorily by a 6M HCl leach; and (*b*) rainwater, foodstuffs and bone, which are best treated by wet or dry ashing with subsequent solution in mineral acid. Following this treatment strontium is radiochemically purified. Y^{90} is allowed to grow to equilibrium, is separated from the parent and measured in a beta counter, thus giving the Sr^{90} content of the sample.[25,26,33-39] The activity of any Sr^{89} present can be determined by difference. A moderately low background counter (5 to 10 cpm) is satisfactory for all samples but human bone, which requires counters with a background of about 1 cpm. The counting procedure must be calibrated with an absolute standard in order to convert the values obtained to disintegration rate. Reference samples for Sr^{90} are available for inter-calibration purposes through the Secretariat of the United Nations Scientific Committee on the Effects of Atomic Radiation and also commercially.[31]

14. The determination of total beta activity involves only preparation of the sample and measurement of the activity. Rainwater activity may be concentrated satisfactorily by evaporation[33,38] or by absorption on ion exchange resins.[23,24] Air filters or the residues from rainwater may be counted directly or dry-ashed prior to measurement of activity.[23,33,38,40] Useful information may be obtained by determination of beta or gamma activity. The conversion of counting data to disintegration rates is difficult; the best standardization is accomplished with mixed fission products from a short irradiation but natural potassium is more generally available and has suitable radiation characteristics.

15. The Cs^{137} burden of humans living in a contaminated environment can best be measured *in vivo* with a whole body spectrometer.[41-45] Gamma spectroscopy is also useful for direct determination of this radioisotope in other materials.[46,47] Radiochemical separation techniques have been described which allow measurement of the caesium beta or gamma activity without energy discrimination.[33,35,38,39] Adequate standards have not been available until recently.[31] An accuracy of $\pm$ 25 per cent may be obtained by comparison of the beta activities of the Cs^{137} with a Sr^{90} standard. An intercomparison programme for development of Cs^{137} standards is desirable.

16. The I^{131} burden in humans can best be measured *in vivo* by scintillation counting of the thyroid with energy discrimination.[48-51] Also, gamma spectroscopy is useful for direct determination of this radioisotope in other materials, though radiochemical techniques have been described which allow measurement of the separated iodine activity.[52,53] Adequate standards are commercially available.[54]

17. The determination of radium involves preparation of a sample solution as for Sr^{90} followed by measurement either by a radon emanation technique[55] or by radiochemical separation and alpha counting of the radium.[56,57] Standards are commercially available.[31,32]

18. The current radiochemical literature describes methods for many other nuclides, (fission products, induced activities, fissionable materials and natural isotopes) which would appear to be completely satisfactory in most instances.

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