UNITED NATIONS

REPORT OF THE UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION

GENERAL ASSEMBLY

OFFICIAL RECORDS : THIRTEENTH SESSION

SUPPLEMENT No. 17 (A/3838)

New York, 1958

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.

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

ANNEXES

Annex D

ENVIRONMENTAL CONTAMINATION

TABLE OF CONTENTS

Paragraph

I. RADIOACTIVE FALL-OUT 1
Fall-out mechanisms 6
Measurement of fall-out 9
Airborne activity 10
Fall-out deposit 12

II. COMPUTATION OF EXTERNAL DOSE FROM FALL-OUT DEPOSIT 20

III. Sr^{90} AS AN INTERNAL SOURCE 26
Evaluation of Sr^{90} as an internal hazard 28
Sr^{90} in soil 29
Sr^{90} in food-chains 33
Discrimination factors 34
The soil-vegetation step in food-chains 37
Concentration of Sr^{90} in foodstuffs 48
Calcium sources in diet 50
Stable strontium sources in diet 52
Daily intake of Sr^{90} in man 53
Sr^{90} in human bone 55
The importance of the stable strontium determination 56
Sr^{90} distribution in different bones of the skeleton 57
Uniformity of Sr^{90} distribution in bone 58
The problem of computing skeleton dose from Sr^{90} 63
Concentrations of Sr^{90} in man 66

IV. Cs^{137} AS AN INTERNAL SOURCE 68
Methods for measurement of concentrations of Cs^{137} 71
Concentrations of Cs^{137} in foodstuffs 73
Daily intake of Cs^{137} in man 74
Concentrations of Cs^{137} in man 75
Dose rate from Cs^{137} in man 76

V. DOSES FROM TROPOSPHERIC FALL-OUT 77
External sources 78
Internal sources 79
Sr^{89} and Ba^{140} as internal sources 80
I^{131} as an internal source 84

VI. ESTIMATION OF DOSES FROM FUTURE FALL-OUT 91
Estimation of fall-out rate and deposit in the future 94
Case 1: Tests stop at the end of 1958 102
Case 2: Tests continue 103
Values of $F_r(0)$ and $F_{\dot{e}}(0)$ 107
Methods for dose estimations 111
External irradiation of gonads caused by Cs^{137} 113
Internal irradiation of gonads caused by Cs^{137} 114
Total irradiation of gonads cause by Cs^{137} 115
Internal irradiation of bone marrow caused by Sr^{90} 116
Estimated doses 124

VII. CALCULATION OF BIOLOGICAL EFFECTS 127
Leukemia, assuming a linear dose response relationship and no threshold 128
Leukemia, assuming a threshold of 400 rem 129
Major genetic defects 130

VIII. NOTE ON INFORMATION DOCUMENT 131

REFERENCES

TABLES

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.

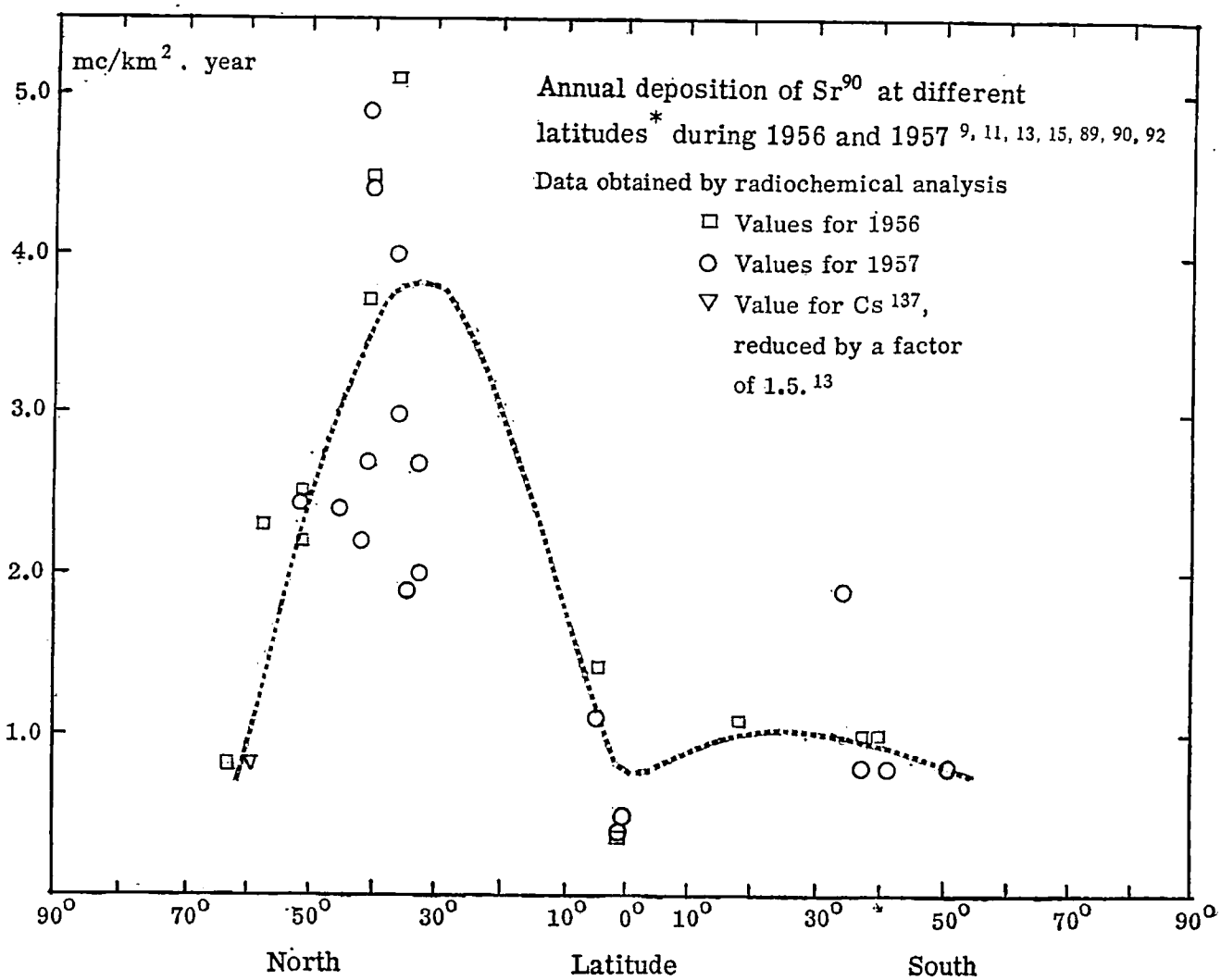

Figure 1. Meteorological factors for the different places of observation have not been taken into account

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:

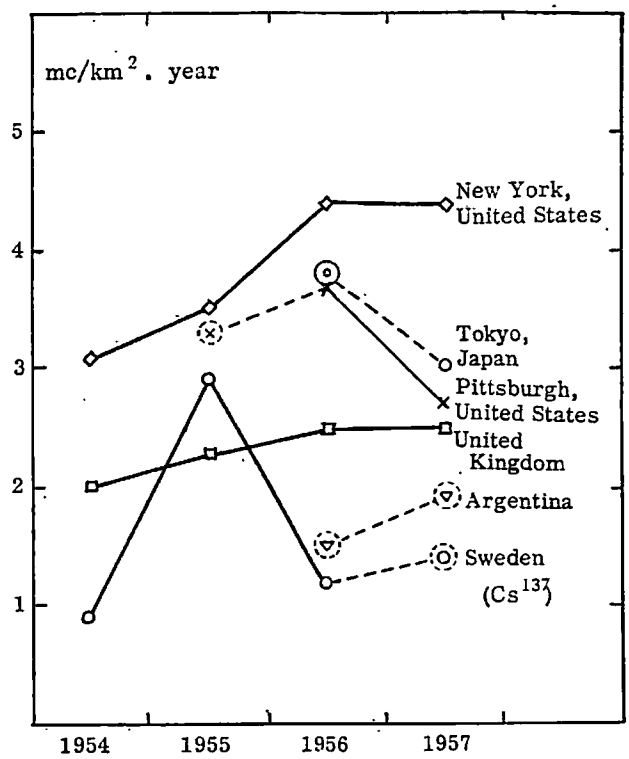

Figure 2. Fall-out rate of Sr^{90} determined by radiochemical analysis.[9,11,15,87,90,92] Values obtained by extrapolation of data for part of year are encircled.

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

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-

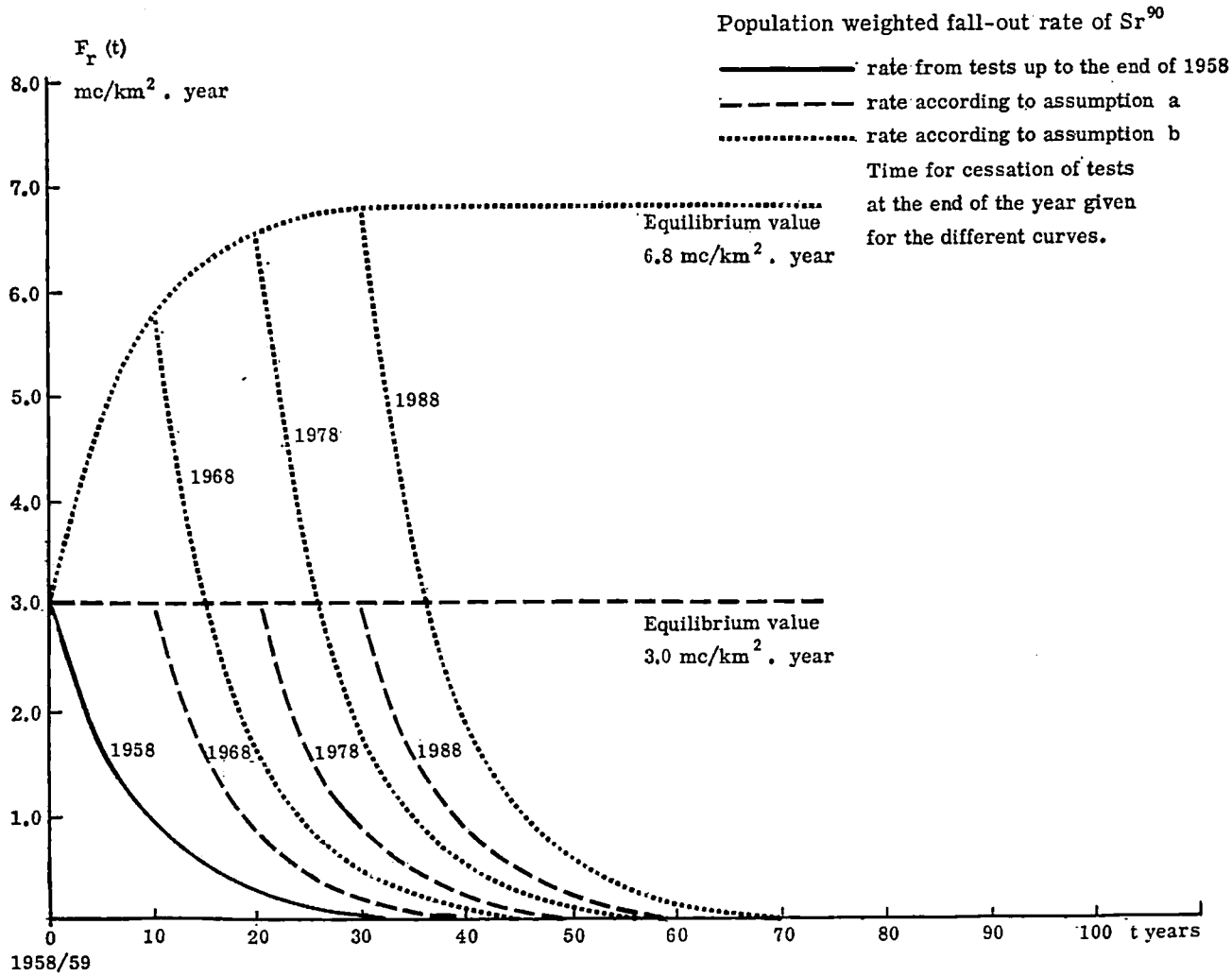

Figure 3

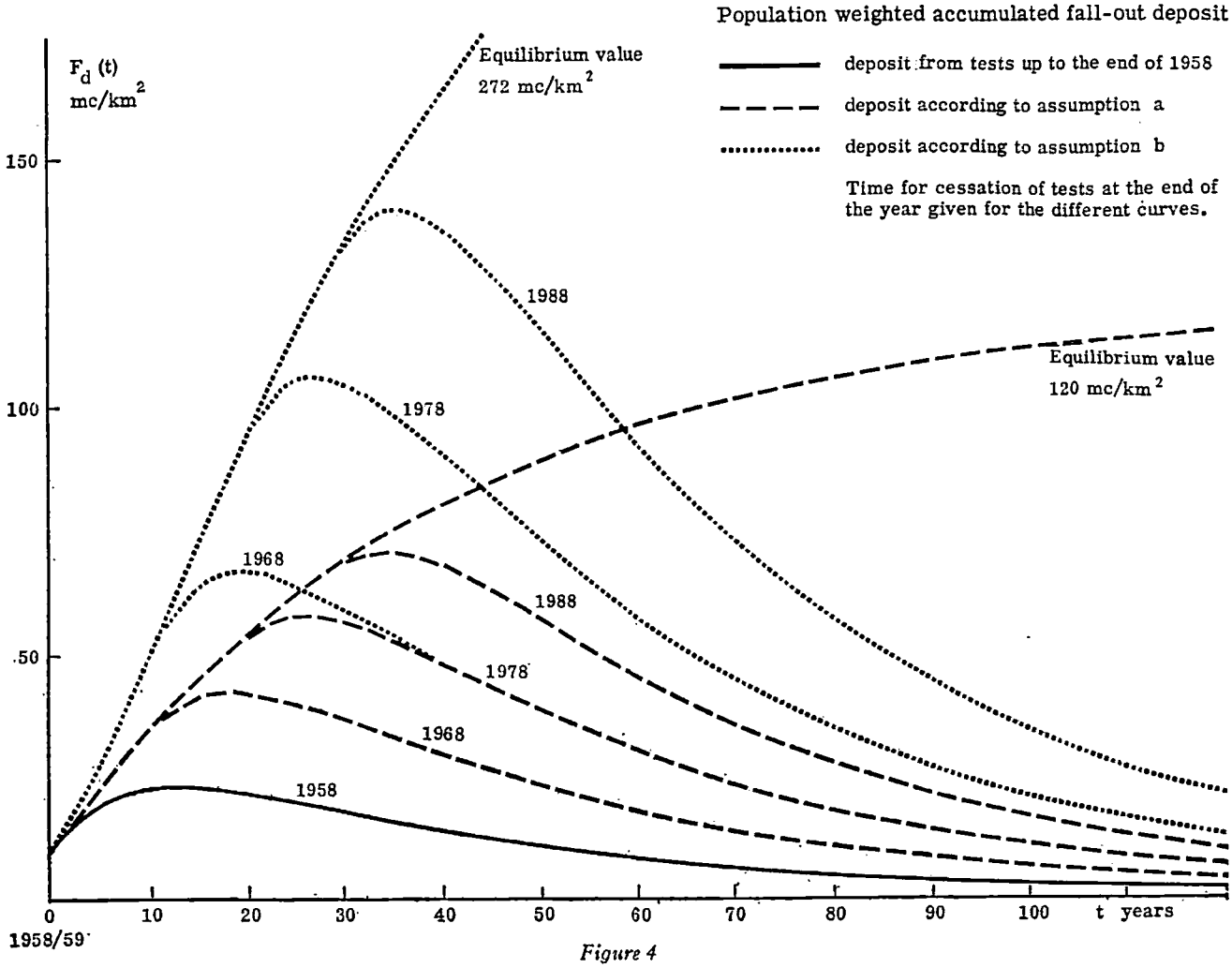

Figure 4

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]

References

1. Marley, W. G., *The long-range fall-out from nuclear test explosions.* Medical Research Council (U.K.): The hazard to man of nuclear and allied radiations, London (1956), p. 121-125. UN document A/AC.82/G/R.2.
2. Stewart, N. G., Crooks, R. N., and Fisher, E. M. R., UN document A/AC..82/G/R.20.
3. Martell, E. A., UN document A/AC.82/G/R.21.
4. Doke, T., UN document A/AC.82/G.R.136.
5. Kurchatov, B. V., UN document A/AC.82/G/R. 199.
6. Aler, B., Björnerstedt, R., Edvarson, K., and Löw, K., UN document A/AC.82/G/R.15. Part 9.
7. Hvinden, T., UN document A/AC.82/G/R.144.
8. Hunter, H. F. and Ballou, N. E., Nucleonics *9*, No. 5. C2-7(1951).
9. Löw, K. and Edvarson, K., UN document A/AC. 82/G/R.146.
10. Eisenbud, M. and Harley, J. H., United States Atomic Energy Commission report HASL-24 (1958).
11. Hardy, Jr., E. P., United States Atomic Energy Commission report HASL-22(1958).
12. Eisenbud, M., *Measurement of strontium-90 in geophysical and biological material.* Hearings before the special subcommittee on radiation of the Joint Committee on Atomic Energy, Congress of the United States. Part 1, 554-575 (1957), and UN document A/AC.82/G/R.130.
13. Stewart, N. G., Osmond, R. G. D., Crooks, R. N., and Fisher, E. M., UN document A/AC.82/G/ R.143.
14. Nussis, N., Henkel, C., and Menis, M., UN document A/AC.82/G/R.157.
15. Miyaka, Y., Sugiura, Y., Saruhashi, K., and Kanazawa, T., UN document A/AC.82/G/R.172.
16. Hallden, N. A., and Harley, J. H., United States Atomic Energy Commission report NYO-4859 (1957), and UN document A/AC.82/INF.1.
17. Aler, B. and Herrlander, C. J., UN document A/ AC.82/G/R.150.
18. Neuman, W. F. and Neuman, M. W.: *Chemical dynamics of bone mineral.* Monograph. University of Chicago Press (1958).
19. Klechkovsky, V. M., editor, UN document A/AC. 82/G/R.41.
20. Harley, J. H., Hardy, Jr., E. P., Whitney, I. B., and Eisenbud, M., UN document A/AC.82/G/R.93.
21. Martell, E. A., UN document A/AC.82/G/R.153.
22. Bryant, F. J., Chamberlain, A. C., Morgan, A., and Spicer, G. S., UN document A/AC.82/G/R.126.
23. Hiyama, Y., editor, UN document A/AC.82/G/ R.141 and Add. 1.
24. Comar, C. L., Scott Russel, R., and Wasserman, R. H., Science *126*, 485-492 (1957).
25. Alexander, G. V., Nusbaum, R. E., and MacDonald, N. S., J. Biol. Chem. *218*, 911-919 (1956).
26. Bryant, F. J., Chamberlain, A. C., Morgan, A., and Spicer, G. S., UN document A/AC.82/G/R.30.
27. Comar, C. L., Whitney, I. B., and Lengemann, F. W., Proc. Soc. Exptl. Biol. Med. *88*, 232-236 (1955).
28. Comar, C. L., Wasserman, R. H., and Nold, M. H., Proc. Soc. Exp. Biol. Med. *92*, 959-863 (1956).
29. Comar, C. L., Wasserman, R. H., Ullberg, S., and Andrew, G. A., Proc. Soc. Exptl. Biol. Med. *95*, 386-391 (1957).
30. Chamberlain, A. C., Spicer, G. S., and Webb, M. S. W., British Medical Journal, in press.
31. Harrison, G. E., Raymond, W. H. A., and Tretheway, H. C., Clin. Sci. *14*, 681-695 (1955).
32. Spencer, H., Laszlo, D., and Brothers, M., J. Clin. Invest. *36*, 680-688 (1957).
33. Eckelman, W. R., Kulp, J. L., and Schulert, A. R., Science *127*, 266-274 (1958).
34. Hiyama, Y.: UN document A/AC.82/G/R.168.
35. Wasserman, R. H., Lengemann, F. W., and Comar, C. L., J. Dairy Science, in press.
36. Comar, C. L. and Wasserman, R. H., Progress in Nuclear Energy. Series VI. Biological Sciences. Pergamon Press, Ltd., London, *1*, 153-196 (1956).

† The values for the 30-year dose have been corrected for tropospheric fall-out in accordance with paragraphs 78 and 79, using a value of 0.5 mrem/year for the period of testing.

37. Libby, W. F., Proc. Natl. Acad. Sci. *42*, 365-390 (1956), and UN document A/AC.82/G/R.131.
38. Wasserman, R. H., Comar, C. L., Nold, M. M., and Lengemann, F. W., Am. J. Physiol. *189*, 91-97 (1957).
39. Lengemann, F. W., Proc. Soc. Exptl. Biol. Med. *94*, 64-66 (1957).
40. Talmage, R. V., Schooley, J. C., and Comar, C. L., Proc. Soc. Exptl. Biol. Med. *95*, 413-417 (1957).
41. Bauer, G. C. H., Carlsson, A., and Lindquist, B., Acta Physiol. Scand. *35*, 56-66 (1955).
42. MacDonald, N. S., Noyes, P., and Lorick, P. C., Am. J. Physiol. *188*, 131-136 (1957).
43. Tajima, E., Science, *in press*.
44. Communicated by W. G. Marley, 1958.
45. Food and Agriculture Organization of the United Nations, UN document A/AC.82/G/R.165.
46. Menzel, R.: Private communication, as given in reference 47.
47. Thurber, D. L., Kulp, J. L., Hodges, E., Gast, P. M., and Wampler, J. M., Science, in press.
48. Canada: Report to the United Nations Scientific Committee on the Effects of Atomic Radiation, UN document A/AC.82/G/R.99.
49. Grummitt, W. E. and Mar, P. G., Atomic Energy of Canada Limited and Department of National Health and Welfare Report CRC 786 (1958).
50. Kulp, J. L. and Slakter, R., Science, *125*, 85-86 (1958).
51. Food and Agriculture Organization of the United Nations, UN document A/AC.82/G/R.76/Rev.1.
52. Argentina: Report to the United Nations Scientific Committee on the Effects of Atomic Radiation, UN document A/AC.82/G/R.127.
53. Hodges, R. H., MacDonald, N. S., Nusbaum, R. E., Stearns, R., Ezmirlian, F., Spain, P., and McArthur, C., J. Biol. Chem. *185*, 519-524 (1950).
54. Turekian, K. K. and Kulp, J. L., Science *124*, 405-407 (1956).
55. Harrison, G. E. and Raymond, W. H. A., J. Nucl. Energy, 290-298 (1955).
56. Sowden, E. M. and Stich, S. R., Biochem. J. *67*, 104-109 (1957).
57. Kulp, J. L., Eckelmann, W. R., and Schulert, A. R., Science *125*, 219-225 (1957) and UN document A/AC.82/G/R.91.
58. Mitchell, H. H., Hamilton, T. S., Steggerda, F. R., and Beau, H. W., J. Biol. Chem. *158*, 625-637 (1945).
59. Hine, G. J. and Brownell, G. L., editors: *Radiation dosimetry*. Academic Press, Inc., New York (1956), p. 899.
60. Hindmarsh, M., Lamerton, L. F., Owen, M., Spiers, F. W., and Vaughan, J., UN document A/AC.82/G/R.114.
61. Engström, A., Björnerstedt, R., Clemedson, C.-J., and Nelson, A.: *Bone and radiostrontium*. Almquist and Wiksell, Stockholm; John Wiley and Son, Inc. New York (1958).
62. Communicated by R. Björnerstedt and A. Engström, 1958.
63. Communicated by W. G. Marley, 1958.
64. Nishita, H., Kowalewsky, B. W., Steen, A. J. and Larson, K. H., Soil Sci. *81*, 317-326 (1956).
65. Anderson, E. C., Schuch, R. L., Fisher, W. R., and Langham, W., Science *125*, 1273-1278 (1957) and UN document A/AC.82/G/R.123.
66. Hood, S. L. and Comar, C. L. University of Tennessee Report ORO-91 (1953), also Arch. Biochem. Biophys. *45*, 423-433 (1953).
67. International Commission on Radiological Protection, Recommendations, revised December 1, 1954. Brit. J. Radiol. Suppl. 6 (1955).
68. Burch, P. R. J., Brit. J. of Radiol. Suppl. 7, 20-26 (1957).
69. Rundo, J., UN document A/AC.82/G/R.167.
70. Sievert, R. M., Proc. Int. Conf. Peaceful Uses Atomic Energy, United Nations *13*, 187-195 (1956).
71. Communicated by I. H. Tipton, 1958.
72. Communicated by W. G. Marley and E. E. Pochin, 1958.
73. Bergh, H., Finstad, G., Lund, L., Michelson, O., and Ottar, B., UN document A/AC.82/G/R.113.
74. Bergh, H., Finstad, G., Lund, L., Michelson, O., and Ottar, B., Norwegian Defence Research Establishment Reports No. KIR-175/57, KIR-176/57, KIR-177/57, KIR-183/57, KIR-186/57, KIR-195/58 (1957-1958).
75. Best, C. H. and Taylor, N. B.: *The physiological basis of medical practice*, 6 ed. The Williams and Wilkins Comp., Baltimore (1955) p. 806-817.
76. Egypt: Preliminary Report to the United Nations Scientific Committee on the Effects of Atomic Radiation, UN document A/AC.82/G/R.46.
77. Gunther, R. L. and Jones, H. B., United States Atomic Energy Commission report UCRL-2689 and addendum, (1954).
78. White, M. R. and Dobson, E. L., United States Atomic Energy Commission report UCRL-3355 (1956).
79. Van Middelsworth, L., Science *123*, 982-983 (1956).
80. Comar, C. L., Trum, B. F., Kuhn III, U.S.G., Wasserman, R. H., Nold, M. M., and Schooley, J. C., Science *126*, 16-18 (1957).
81. Communicated by W. G. Marley, 1958.
82. Hine, G. J. and Brownell, G. L., editors: *Radiation dosimetry*. Academic Press Inc., New York (1956) p. 868.
83. Dunning, G. M., Nucleonics *14*, No. 2, 38-41 (1956).
84. Communicated by L. Machta, representative of the World Meteorological Organization to the United Nations Committee on the Effects of Atomic Radiation, 1958.
85. Lewis, C.: *The American Oxford Atlas*. Oxford University Press, New York (1951).
86. Sievert, R. M., Gustafsson, S., and Rylander, C. G., Arkiv för fysik *12*, 481-499 (1957) and UN document A/AC.82/G/R.147.
87. Alba, F., Brody, T., Palacios, A., and Tejera, A., UN document A/AC.82/G/R.187.
88. Data submitted by the United States delegation to the United Nations Committee on the Effects of Atomic Radiation (1958).
89. Data submitted by the United Kingdom delegation to the United Nations Committee on the Effects of Atomic Radiation (1958).
90. Data submitted by the Japanese delegation to the United Nations Committee on the Effects of Atomic Radiation (1958).

91. Communicated by W. E. Grummitt, 1958.
92. Hardy, Jr., E. P., United States Atomic Energy Commission Report HASL-38 (1958).
93. Communicated by J. H. Harley, 1958.
94. Alba A., F., Brody, T. A., Cameras, R., Palacios, A., Rickards C., G., Tejera R., A., and de Velarde, E. G. B., UN document A/AC.82/G/R.164.
95. Blok, J., UN document A/AC.82/G/R.184.
96. Russell, R. S. and Milbourn, G. M., Nature, *180*, 322-324 (1957).
97. UN document A/AC.82/INF.3. Copies of the document may be obtained by writing to the United Nations, New York 17, N. Y., U.S.A.

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.

Appendix

LIST OF SCIENTIFIC EXPERTS

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

ARGENTINA:
- Dr. C. Nuñez *(Representative)*
- Dr. D. J. Beninson
- Professor E. Favret
- Dr. N. Nussis
- Dr. J. A. Olarte

AUSTRALIA:
- Dr. C. F. Eddy *(Representative—first session)*
- Mr. D. J. Stevens *(Representative)*
- Dr. A. R. W. Wilson

BELGIUM:
- Professor Z. Bacq *(Representative)*
- Mr. R. Boulenger
- Dr. M. Errera
- Professor F. Twisselman

BRAZIL:
- Professor C. Chagas *(Representative)*
- Dr. B. Gross
- Professor N. Libanio
- Professor C. Pavan
- Father F. X. Roser, S.J.

CANADA:
- Dr. E. A. Watkinson *(Representative)*
- Dr. R. K. Appleyard
- Dr. P. M. Bird
- Dr. W. E. Grummitt
- Dr. Colin Hunter
- Dr. G. H. Josie
- Dr. C. A. Mawson
- Dr. H. B. Newcombe
- Dr. F. D. Sowby

CZECHOSLOVAKIA:
- Professor F. Herčík *(Representative)*
- Professor F. Běhounek
- Dr. M. Hašek
- Dr. L. Novák
- Professor V. Sobek
- Dr. I. Ulehla
- Dr. V. Zelený

EGYPT*
- Dr. A. Halawani *(Representative)*
- Dr. H. T. Daw

FRANCE:
- Professor L. Bugnard *(Representative)*
- Dr. A. Allisy
- Dr. J. Coursaget
- Dr. H. Jammet
- Dr. J. Labeyrie
- Dr. J. Lejeune

INDIA:
- Dr. V. R. Khanolkar *(Representative)*
- Dr. A. R. Gopal-Ayengar
- Dr. A. S. Rao

JAPAN:
- Dr. M. Tsuzuki *(Representative)*
- Dr. Y. Hiyama
- Dr. D. Moriwaki
- Dr. K. Murati
- Dr. M. Nakaidzumi
- Mr. S. Ohta
- Dr. N. Saito
- Dr. E. Tajima

MEXICO:
- Dr. M. Martínez Báez *(Representative)*
- Dr. F. A. Andrade
- Dr. H. Zalce

SWEDEN:
- Professor R. M. Sievert *(Representative)*
- Dr. B. A. A. Aler
- Dr. R. G. Björnerstedt
- Professor G. Bonnier
- Professor T. O. Caspersson
- Professor C. A. T. Gustafsson
- Dr. A. G. A. Nelson

* Now in the United Arab Republic.

UNION OF SOVIET SOCIALIST REPUBLICS:

Professor A. V. Lebedinsky *(Representative)*
Professor K. K. Aglintsev
Professor B. M. Isaev
Professor P. M. Kireev
Professor A. N. Kraevsky
Professor A. M. Kuzin

UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND

Professor W. V. Mayneord *(Representative—first session)*
Dr. E. E. Pochin *(Representative)*
Dr. T. C. Carter
Mr. A. C. Chamberlain
Dr. W. G. Marley
Mr. N. G. Stewart

UNITED STATES OF AMERICA:

Dr. Shields Warren *(Representative)*
Professor G. W. Beadle
Dr. A. M. Brues
Professor J. Crow
Professor Th. Dobzhansky
Dr. C. L. Dunham
Mr. Merril Eisenbud
Professor Sterling Emerson
Professor G. Failla
Dr. J. H. Harley
Dr. J. S. Laughlin
Professor J. V. Neel
Dr. M. Zelle

back to first page