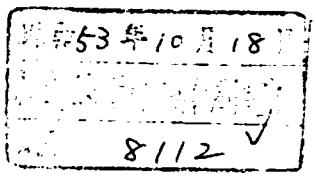
1977年報告

SOURCES AND EFFECTS OF IONIZING RADIATION

United Nations Scientific Committee
on the Effects of Atomic Radiation

1977 report to the General Assembly, with annexes



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NOTE

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ANNEX C

Radioactive contamination due to nuclear explosions

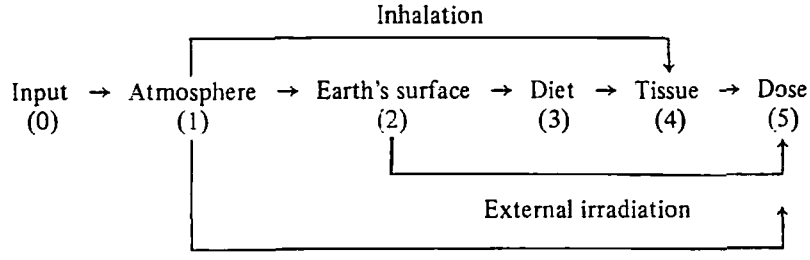
CONTENTS

Introduction

1. During the period reviewed in this report (January 1972 to December 1976) a number of nuclear tests have been reported, including 20 atmospheric tests, 6 of which were in the northern hemisphere and 14 in the southern hemisphere. In this Annex, therefore, the total inventory of radionuclides from nuclear tests has been reassessed and the consequential changes in the dose commitments have been evaluated.

2. This Annex also discusses improvements in the knowledge of the parameters involved in the assessment of dose commitments, particularly those factors related to the transfer of radioactivity between compartments

of the environment linking the input of radionuclides to the subsequent dose in man. The compartment model used by the Committee in its assessments can be represented schematically as follows:



This model does not include all possible pathways of human exposure, but only those relevant to the assessments presented in this Annex. Procedures for the use of the model are described in Annex A.

3. Where sufficient information is available, assessments of collective dose commitments per unit activity release are presented. It should be noted that the bulk of the radionuclides from atmospheric nuclear explosions was injected into the atmosphere at high altitude. For this reason many of these commitments per unit activity do not apply to other situations of environmental releases of radioactive materials.

I. TRANSPORT OF RADIOACTIVE DEBRIS WITHIN THE ATMOSPHERE

4. During a nuclear explosion, the fission products, residual fissile material and structural materials associated with the device are raised to sufficiently high temperatures to be present in gaseous form. For explosions detonated in the atmosphere near the surface of the earth, a considerable amount of volatilized soil or rock material may also be entrained in the fireball.

5. After the explosion in the atmosphere, the fireball expands rapidly and rises due to buoyancy. As it rises, cooling causes the volatilized debris to condense, forming an aerosol with a wide distribution in particle size (245).

6. The height to which the aerosol cloud rises increases with explosion yield. Since the height of the tropopause is lower in polar regions than near the equator, the extent to which the cloud enters the stratosphere will depend on both latitude and yield (201).

7. During the initial expansion of the fireball, some tens of seconds after detonation, particles composed of iron and aluminium oxides and of other refractory materials are formed, with diameters in the range 0.4-4.0 μm (81, 223). The radionuclides having the more refractory oxides (i.e., oxides with high boiling points), tend to be incorporated into these particles, while those that have low boiling point oxides tend to be excluded. When the refractory material has condensed out, the gaseous remainder, enriched in the more volatile radionuclides and in radionuclides with volatile precursors, condenses into small particles (diameter < 0.4 μm). This separation of the radionuclides between aerosol particles in the two size ranges is usually known as fractionation. Because the larger aerosol particles are subjected to significant gravitational settling, they are more likely to be deposited upon the earth near the explosion site, whereas the smaller aerosol particles remain at greater altitudes for a longer time and are distributed over a wider area (95).

8. When nuclear explosions are detonated on or near the ground, large amounts of soil or rock materials are drawn into the fireball. On cooling, these tend to form large aerosol particles; so for surface detonations much of the radioactive material is present in relatively large aerosol particles.

9. Radioactivity present in large aerosol particles will fall out within a few hundred kilometres, constituting the "local fallout"; smaller aerosol particles injected into the lower troposphere can be transported around the earth in the same hemisphere, and will be deposited from hundreds to many thousands of kilometres from the detonation site, constituting the "tropospheric fallout". Aerosol particles carried up into the stratosphere give rise to fallout with a world-wide distribution, the major part of which is in the hemisphere of injection. This fallout is known as global or "stratospheric" fallout.

10. Most of the world-wide contamination of long-lived fission products has been from the stratospheric fallout resulting from large thermonuclear tests. On the other hand, tropospheric fallout accounts for much of the contamination from short-lived radionuclides, during the first few months after a test.

11. Our knowledge of mixing processes and air movements in the stratosphere is still incomplete, although many of the gross features are now known from studies of radionuclide concentrations. Detailed descriptions of the atmospheric movement of radionuclides were given in the Committee's 1964 and 1972 reports (242, 245). Mixing processes in the stratosphere are generally slower than in the troposphere, most of the movement being due to horizontal diffusion with considerable downward motion at higher latitudes in the winter hemisphere (153).

12. Several mechanisms account for the transfer of particulate radioactivity from the stratosphere to the troposphere. Prominent among these is the horizontal transfer through the subtropical tropopause gap. This

transfer process reaches a maximum in late winter and gives rise to the well known spring maximum in the fallout rate (141).

13. The mean residence time of a radionuclide in the stratosphere, defined as the average time spent by atoms of that radionuclide in the stratosphere before transfer to the troposphere, depends on the latitude and altitude of injection and also on the time of the year at which the injection is made. Between 15 and 25 km altitude, the mean residence time can vary from 0.3 to 2 y, depending upon altitude and latitude (212). For ^{90}Sr, the mean residence time in the stratosphere is typically of the order of 1 y (242). The long effective mean residence time in the stratosphere observed for some radionuclides such as ^{14}C is due to the fact that these radionuclides are not removed rapidly from the troposphere and are recycled back into the stratosphere (211).

14. After the radioactive debris has entered the troposphere, it is rapidly dispersed throughout the hemisphere. For particulate radioactivity, the troposphere is rapidly depleted by essentially three processes: *(a)* rain-out caused by droplet formation within clouds, *(b)* wash-out by falling raindrops picking up radioactivity, and *(c)* dry deposition on land surfaces or plant cover, this last process being of more importance in dry regions (85, 140). The resulting residence time for particulate radioactivity in the troposphere is about 30 d (98, 154, 176). Because of this rapid removal, very little particulate activity moves from the troposphere of one hemisphere to the troposphere of the other. On the other hand, gaseous radionuclides in the troposphere, such as ^{85}Kr, mix between hemispheres with a mean exchange time of 1.5 y (242).

II. INTERNAL IRRADIATION

A. TRITIUM

15. Tritium, a radioactive isotope of hydrogen, is a pure beta emitter with maximum energy of 0.018 MeV and a half-life of 12.3 y. It occurs naturally on the earth's surface, being produced in the stratosphere by reactions induced by cosmic rays (Annex B). Man-made tritium, in amounts substantially larger than the natural inventory, has been injected into the stratosphere by thermonuclear explosions. Most of this tritium is in the form of water (as HTO) and, after a mean residence time of about a year, enters the troposphere, and then the hydrological cycle. Tritium has been extensively monitored in precipitation and natural waters. In 1961, IAEA established a world-wide network for monitoring the ^{3}H concentration in precipitation (133).

1. Tritium inventory

16. From a study of ^{3}H concentrations in profiles in the Pacific Ocean at stations from latitude 60° S to 51° N, Michel (167) has estimated the world's ^{3}H inventory in 1970 to be 2900 MCi, which when corrected for decay using the annual deposition of ^{90}Sr as a guide, gives a total injection of ^{3}H of 4500 MCi. According to Michel's estimates, about 20 per cent of this is in the southern hemisphere, so it is estimated that 3600 MCi and 900 MCi of ^{3}H were released into the northern and southern hemisphere, respectively. It is also possible to estimate the ^{3}H inventory from measured ^{3}H and ^{90}Sr activities in ocean waters. Bowen and Roether (46) have reported total ^{3}H and ^{90}Sr inventories in the profiles at five sites in the Atlantic Ocean between latitude 35° and 45°. The average ^{3}H-to-^{90}Sr activity ratio at these five sites was 325.6. The cumulative deposit of ^{90}Sr in the northern hemisphere in 1970 was 9.37 MCi, and since the ocean makes up 56 per cent of the area of the northern hemisphere, 5.25 MCi of ^{90}Sr will be in the northern hemisphere oceans. Using the above value for the $^{3}H/^{90}Sr$ ratio, it is estimated that $5.25 \times 325.6 = 1708$ MCi of ^{3}H were present in oceans of the northern hemisphere in 1970. Correcting for radioactive decay it is estimated that some 2740 MCi of ^{3}H were released in the northern hemisphere, since it can be assumed that most fallout tritium on land has been washed into the oceans. Using the partitioning of ^{90}Sr between hemispheres as a guide, the inventory of ^{3}H in the southern hemisphere is estimated to be 820 MCi.

17. Both the above estimates are larger than that of Eriksson (1900 MCi) reported in the Committee's 1972 report, but much lower than the 8000 MCi reported by Miskel (84, 173). the latitudinal distribution of tritium in surface waters of the Pacific between 1965 and 1972 is shown in figure I (167). From concentrations in precipitation at stations in the IAEA network, Schell *et al.* (20) estimated the deposition between 1963 and 1969 to be 1780 MCi in the northern hemisphere and about 400 MCi in the southern hemisphere. Using the annual global deposition of ^{90}Sr as a guide, these results indicate that the total injection of ^{3}H up to 1970 was about 4500 MCi, in agreement with the estimate from Michel's data.

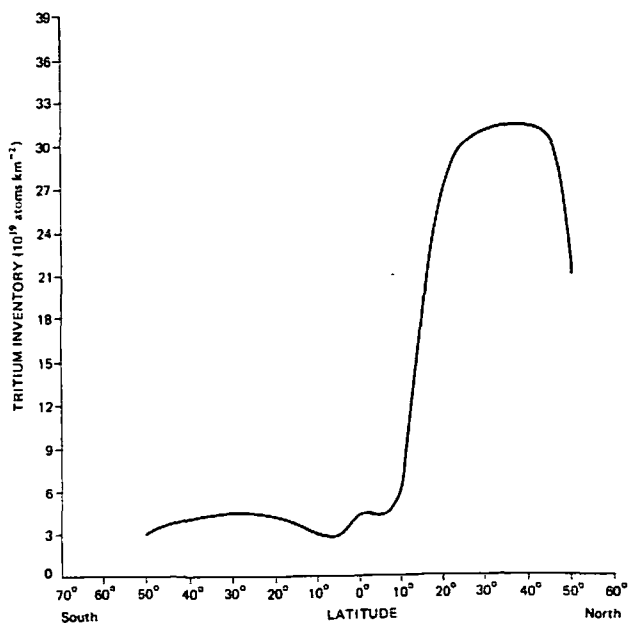


Figure I. Latitudinal distribution of the tritium inventory per unit area in the top 500 m of the Pacific Ocean, 1965-1972 (167)

2. Dose commitment from tritium

18. In the 1972 report, the dose commitments from fallout tritium were estimated in an indirect way on the basis of a comparison with the production rate of natural tritium and the measured concentrations in waters prior to the commencement of thermonuclear tests. More recent papers dealing with fallout tritium make it possible to estimate the dose commitments directly from fallout measurements. It should be realized that, due to insufficient information relating to some of the quantities involved in the calculations, estimates by both methods are uncertain.

19. Bennett (25, 37) used a three-compartment model suggested by Sanders and Reinig (219) to determine the tissue dose rate at equilibrium for a continuous intake of tritium in water. This model considers the dose rate in tissue due to tritium in tissue water as well as that which is organically bound in tissue. For a chronic intake of water with a concentration of 1 μCi l^{-1}, the tissue dose rate at equilibrium is 95 mrad y^{-1}. Of this, 84 per cent is due to tritium in water and 16 per cent to tritium combined in tissue.

20. The tritium activity concentration of surface waters in the United States of America is shown in figure II. From the tritium concentrations in 18 United States rivers and in the Ottawa river, Bennett (25, 37) estimated the whole body dose commitments to the populations of the United States and the Ottawa Valley to be 1.5 and 2.8 mrad, respectively.

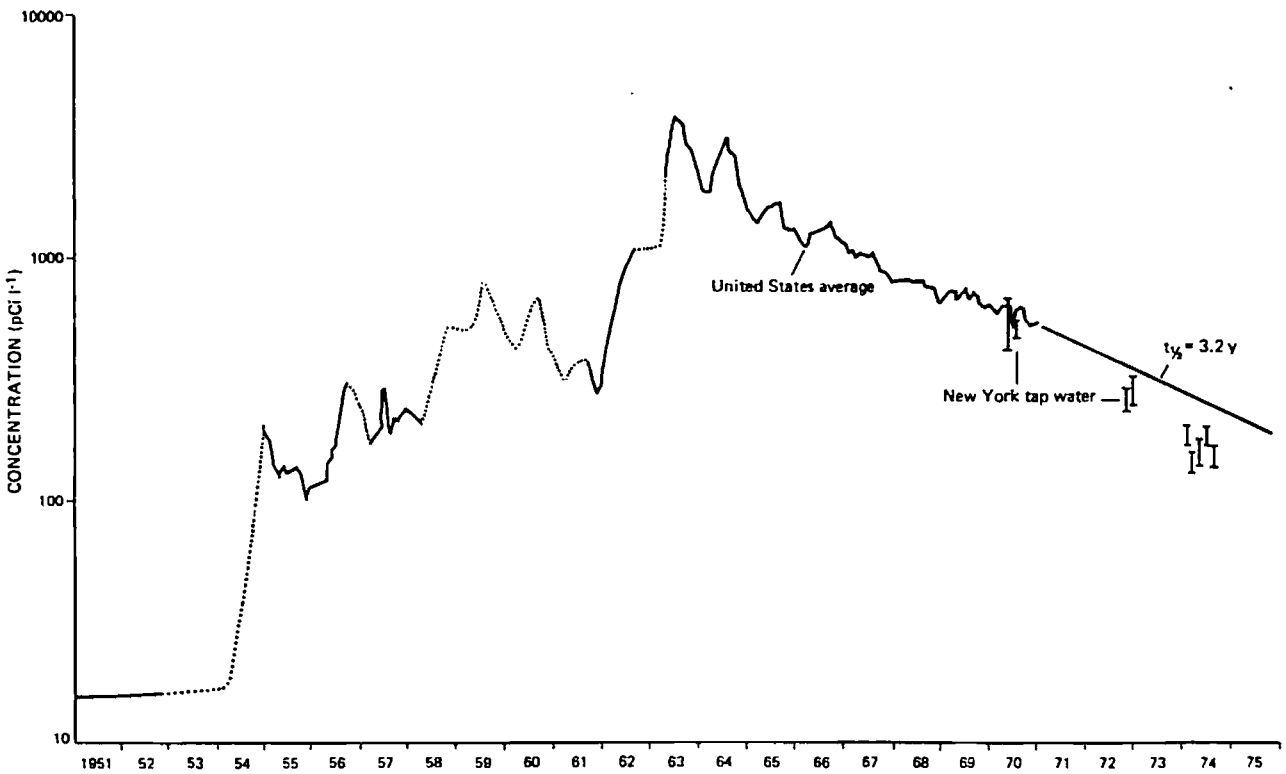


Figure II. Variation of tritium activity concentration of surface waters in the United States of America over the period 1951-1975 (25, 27)

21. Schell *et al.* (220) have evaluated the 1961 to 1967 data provided by the IAEA and WMO world survey of tritium concentration in precipitation. They observed that the latitudinal distribution of the tritium concentration in precipitation at marine stations increased exponentially from the equator to the polar regions. In the northern hemisphere, the concentration doubled about every 13° of latitude, and in the southern hemisphere, about every 16° of latitude. The concentrations observed at the continental stations were on the average higher than at the marine stations by a factor of 3.6, this effect being due partly to re-evaporation and evapotranspiration over the land mass and partly to greater injection.

22. Assuming that the dose commitment to a population living in a given latitude band is proportional to the concentration in the corresponding precipitation and that the average concentration doubles every 13° of latitude from the equator to the North Pole, a dose commitment of 2.8 mrad to the Ottawa Valley population corresponds to a dose commitment to the population of the northern hemisphere of 2.0 mrad.

23. From the extensive measurements of the tritium concentration in rainwater in both hemispheres between 1964 and 1967 carried out by IAEA (220), it appears that on the average the concentrations in the southern hemisphere were about one tenth of those in the northern hemisphere. Assuming that this ratio applies over the whole period of atmospheric tests, the dose commitment to the population of the southern hemisphere is estimated to be 0.2 mrad.

24. The dose commitment from fallout tritium can also be assessed, as in the 1972 report, using the relation $D^c = \gamma_0 W/B$, where D^c is the dose commitment, γ_0 is the tissue dose rate from natural tritium, W is the activity of tritium released by nuclear explosions, and B is the activity of natural tritium produced annually.

25. The annual dose from natural tritium is estimated to be 1.0 μrad (Annex B). Assuming a total release in the northern hemisphere of 3600 MCi of tritium from nuclear explosions, as discussed in previous paragraphs, and an annual natural production per hemisphere of about 1.9 MCi (Annex B), the dose commitment in the northern hemisphere from fallout tritium is estimated to be 1.9 mrad. In the southern hemisphere the dose commitment estimated by the same procedure is 0.47 mrad.

26. These values are in reasonable agreement with those given in paragraphs 22 and 23, namely 2 mrad and 0.2 mrad, which are taken in this report as the dose commitments from tritium in the northern and southern hemisphere, respectively. These estimates are lower than those presented in the 1972 report (4 mrad for the northern hemisphere and 1 mrad for the southern hemisphere).

27. The collective dose commitment from tritium is dominated by the contribution from the northern hemisphere, because of the higher individual doses in that hemisphere and also because of population distribution. Using the procedures outlined in Annex A and assuming a population growth of 2 per cent per year, the collective dose commitment due to tritium from nuclear explosions is estimated to be about $8\ 10^{6}$ man rad, corresponding to about $3\ 10^{-3}$ man rad per curie of released activity. It should be noted that this estimate applies to the injection of tritium by nuclear explosions carried out in the northern hemisphere.

B. CARBON-14

28. Carbon-14 is a pure beta emitter with a maximum energy of 0.156 MeV and a half-life of 5730 y. It is formed in atmospheric nuclear explosions from the capture of excess neutrons by nitrogen. After large atmospheric nuclear explosions, most of the ^{14}C is transported into the stratosphere, from where it equilibrates with the troposphere with a half-time of 1-2 y.

29. Present in the troposphere as carbon dioxide, the activity of ^{14}C reached a peak in 1965 as a result of the nuclear explosions in the late 1950s and early 1960s. Although there have been additions to the troposphere of ^{14}C from explosions since that time, these inputs have been smaller than uptake by the oceans and the biosphere, and thus the levels in the troposphere have continued to decrease.

30. Measured values of excess specific activity of ^{14}C in the troposphere and in the surface ocean are shown in figure III. In order to estimate the inventory of ^{14}C from nuclear explosions and to predict future atmospheric levels, some model to represent the exchange of ^{14}C between the atmosphere, biosphere and ocean is needed.

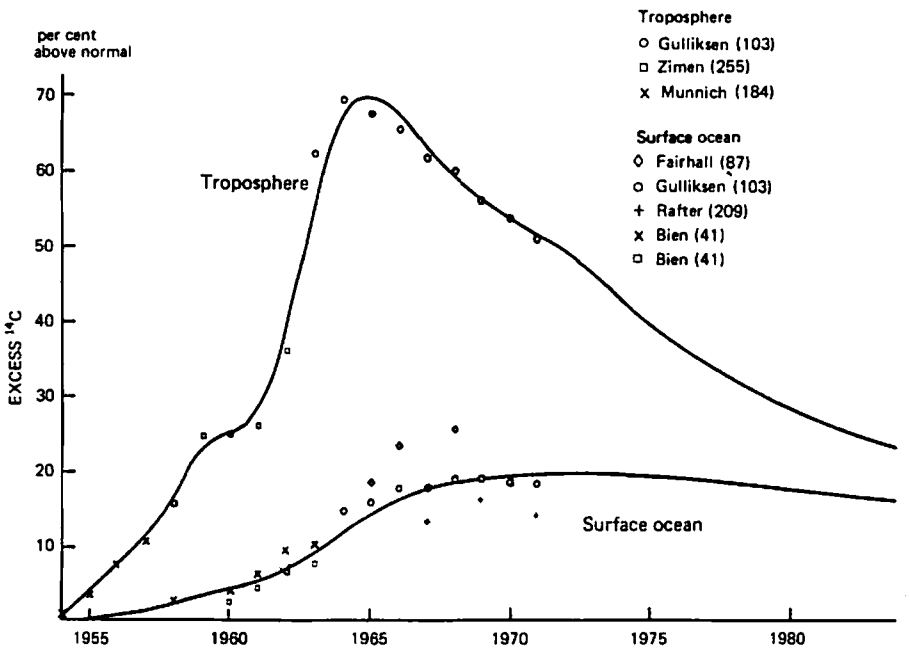


Figure III. Variation of excess ^{14}C in the troposphere and surface ocean. (The continuous line has been obtained by regression, assuming no injections after 1972)

31. Figure IV is a schematic representation of the model used in this report to predict the circulation of ^{14}C and of the excess stable carbon injected by the use of fossil fuels (196). This model is similar to previous models used by the Committee except that the thermocline region of the ocean is represented as a diffusive layer (194, 208, 242). The values of the relevant parameters are also shown in this figure. The parameters K_a, k and W_t were adjusted to fit the excess ^{14}C in the atmosphere and surface ocean. Since the transfer time between the atmosphere and the short-term biosphere (i.e., annual plants, leaves, and short-term detritus) is short, being about 2.5 y, for the purposes of these calculations the short-term biosphere

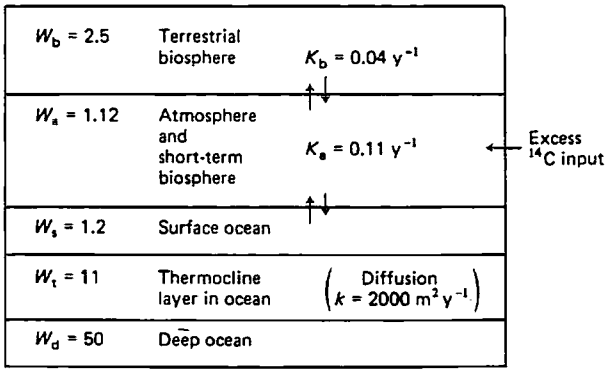


Figure IV. Model representing the exchange of excess ^{14}C between the atmosphere, the biosphere and the ocean. The factors W are the capacity of each reservoir in units of the atmospheric capacity. The parameters K_b and K_a are transfer rates and k is a diffusion coefficient.

is combined with the atmospheric compartment (13). The mean residence time of the excess ^{14}C in the atmospheric and short-term biospheric compartments, before movement to the long-term biospheric compartment or to the oceans, is $W_a/(K_a + K_b) = 7.5$ y.

32. The predicted values of the excess ^{14}C in the atmosphere and surface ocean are included in figure III. The parameters of the model, obtained by regression from the actual data on excess of ^{14}C, indicate that the input of man-made ^{14}C into the atmosphere up to 1972 was 5.8 MCi, and that the time-integrals of the man-made ^{14}Ccontent in the atmosphere up to 2000, 2020 and 2050 are equivalent to the natural content multiplied by 14.4, 17.1 and 20.5 y, respectively. Fairhall *et al.* (87), using a quite different approach, estimated the excess ^{14}C inventory up to 1971 to be 6.2 MCi.

33. Carbon-14 is taken up by plants during photosynthesis and is subsequently incorporated into the human body. Several investigators have measured excess ^{14}C levels in human tissue (81, 150). Nydal *et al.* (194), from the measurement of ^{14}C/^{12}C ratios in human hair and blood between 1962 and 1969, concluded that the specific activity in human tissue comes into equilibrium with that in atmospheric CO_2 with a delay time of about 1.4 y.

34. The dose commitment from man-made ^{14}C can be assessed, as shown for the case of tritium, by a comparison with natural ^{14}C. Taking the natural production rate to be 28 kCi y^{-1}, as derived from the natural ^{14}C inventory, and the tissue dose rates from natural ^{14}C (Annex B), the dose commitments shown in table 1 have been calculated.

TABLE 1. DOSE COMMITMENTS FROM THE ^{14}C PRODUCED IN NUCLEAR EXPLOSIONS

(mrad)

	Gonads	*Lung*	*Bone lining cells*	*Red bone marrow*	*Whole-body average*
Dose commitment	103	124	414	455	269
Part accumulated up to:					
2 000	7.2	8.6	29	32	19
2 020	8.6	10.3	34	38	22
2 050	10.2	12.2	41	45	27

35. The parts of the dose commitment to the world population from ^{14}C delivered up to 2000, 2020 and 2050 were estimated from the corresponding integrated atmospheric levels given in paragraph 32. They are also shown in table 1.

36. Assuming an upper limit of 10^{10} for the world population, the collective dose commitment per unit activity of ^{14}C released in the stratosphere is estimated to be about 200 man rad Ci^{-1} for soft tissues and about 700 man rad Ci^{-1} for bone lining cells and for red bone marrow.

C. MANGANESE-54

37. Manganese-54 was a significant component of fallout activity for several years after the test series in 1961-1962. It is not a fission product and was presumably produced by neutron capture reactions in the structural material used in the nuclear devices. It has a half-life of 310 d, decaying by electron capture with the emission of gamma and x rays. Little activity has been measured in air since 1966. The time-integrated activity concentration in air measured at Sterling, Virginia (United States), between 1963 and 1966 was 1.13 pCi y m^{-3} (117, 249), and is typical of the integrated values measured in temperate latitudes of the northern hemisphere. In the southern hemisphere, the values were 100 times lower. Measurements of the deposition density (the activity deposited per unit area) made at Westwood, New Jersey (United States), indicate indirectly that the integrated air concentrations in 1962 were about 10 per cent of those in 1963 (110). Using this information, the integrated activity concentration in air at Sterling, Virginia, for 1962-1974 is estimated to be 1.2 pCi y m^{-3}.

38. Voilleque and Pelletier (248) have considered the different pathways of ^{54}Mn to man and have estimated transfer factors for the pathway air → deposition on the ground → cow's milk → man. In man, the organ receiving the highest dose from ingestion is the lower large intestine. For adults, the transfer factor P_{12345} pertaining to the atmosphere-to-dose pathway via ingestion (see paragraph 2), is estimated to be $7\ 10^{-3}$ mrad per pCi y m^{-3}. For children less than one year old, the population group receiving the highest dose, these authors estimated P_{12345} to be 0.11 mrad per pCi y m^{-3}. The main dose is in the lung due to direct inhalation. Using the ICRP lung model (134, 135, 136) with the set of parameters for compounds class W, and a value of 20 per cent retention in the pulmonary region, the value of P_{145} for adults is 0.91 mrad per pCi y m^{-3}. The dose commitments from ^{54}Mn, assessed from the factors mentioned above, are $8\ 10^{-3}$ mrad to the lower large intestine (LLI) of adults, 0.16 mrad to the LLI of infants, and 1.0 mrad to the adult lung.

D. IRON-55

39. Iron-55 has a half-life of 2.7 y and decays by electron capture with the emission of x rays and bremsstrahlung with 0.23 MeV maximum energy.

Iron-55 was produced as an activation product in the nuclear tests carried out in 1961-1962 and it is estimated that a total of about 50 MCi was produced (126). The concentration of ^{55}Fe in air fell rapidly after 1962-1963 and has been essentially zero since 1970. Time-integrated concentrations in the atmosphere of the southern hemisphere were considerably below those of the northern hemisphere.

40. The uptake of ^{55}Fe by man was discussed in the 1972 report of the Committee (245), and it appears that both the terrestrial food chain and the marine food chain leading to man are important in contributing to the activity in man (137, 197). Body activities measured in a large number of people in different parts of the world in 1966 were in the range 20-30 nCi, and they dropped to 1-10 nCi in 1969 (148, 197). In Japan and in Alaska (United States) in 1966, body activities greater than 1000 nCi were observed in persons consuming large quantities of fish (197). The dose commitments in the northern hemisphere from testing in the period 1954-1962 was estimated by Persson (199), assuming a maximum body activity of 30 nCi in the temperate latitudes. The estimates are 1 mrad to the gonads and bone lining cells and 0.6 mrad to the bone marrow. A reduction by a factor of four is assumed for the southern hemisphere. The collective dose commitment per unit activity released in the northern stratosphere is estimated to be about $6\ 10^{-2}$ man rad Ci^{-1} for the gonads and bone lining cells and $4\ 10^{-2}$ man rad Ci^{-1} for the bone marrow.

E. KRYPTON-85

41. The production of ^{85}Kr by nuclear explosions can be estimated from ^{90}Sr production values, using a $^{85}Kr/^{90}Sr$ fission-yield ratio of 0.07 (164, 190). By this procedure the production of ^{85}Kr by nuclear explosions is estimated to be about 3 MCi. Krypton-85 is an inert gas and most of it remains in the atmosphere, its concentration becoming fairly uniform throughout the earth's atmosphere within a few years (88). Most of the ^{85}Kr present in the earth's atmosphere originates in releases from nuclear-fuel reprocessing plants and not from nuclear explosions (Annex D).

42. Krypton-85 has a 10.7-y half-life, is a beta emitter with a maximum energy of 670 keV, and emits a 514-keV photon in 0.4 per cent of the disintegrations. The dose to the skin, lung and gonads from a time-integrated concentration in air of 1 pCi y m^{-3} have been estimated (185) to be 1.8 μrad, $3.1\ 10^{-2}$ μrad and $1.6\ 10^{-2}$ μrad, respectively. Assuming that 3 MCi are uniformly mixed in the earth's troposphere ($5\ 10^{21}$ g air), the resulting dose commitments are estimated to be 21 μrad, 0.35 μrad and 0.2 μrad for the skin, lung and gonads, respectively. Assuming an annual increase in the world population of 2 per cent, the collective dose commitments, per curie of ^{85}Kr released in the stratosphere, are estimated to be about $4\ 10^{-3}$ man rad for skin, $7\ 10^{-4}$ man rad for lung and $4\ 10^{-4}$ man rad for gonads.

F. STRONTIUM-90

1. Inventory and deposition

43. Strontium-90, a pure beta emitter with a maximum energy of 0.54 MeV, decays with a half-life of 28 y to ^{90}Y, which has a half-life of 65 h and is a beta-emitter with a maximum energy of 2.27 MeV.

44. The total stratospheric inventory of ^{90}Sr is shown in figure V, together with that for each hemisphere for the period 1963-1975 (149). The period between 1963 and 1966 was marked by an exponential decrease of the

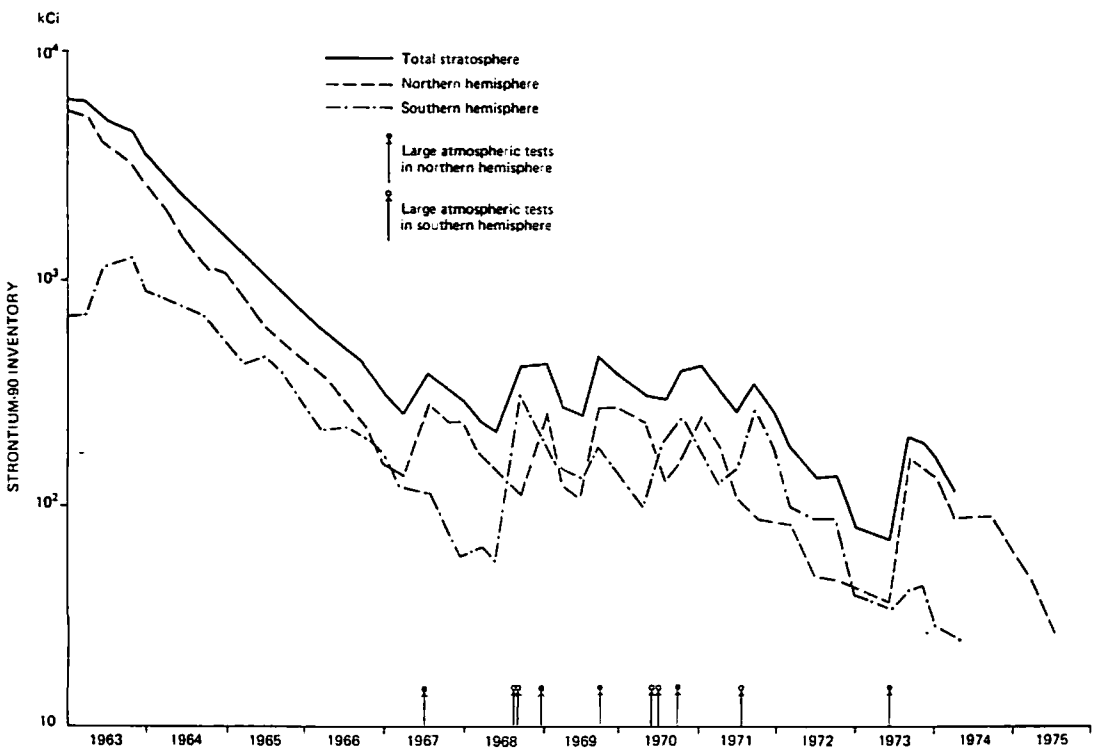


Figure V. Variation of the stratospheric inventory of ^{90}Sr over the period 1963-1975 (149)

stratospheric inventory from the peak value resulting from the atmospheric tests conducted in the early 1960s. Between 1966 and mid-1971, the inventory in each hemisphere remained fairly constant at about 20 per cent of the 1963 peak values. During this period, the northern and southern hemisphere stratospheres were replenished with ^{90}Sr from a series of tests carried out in central Asia and in the south Pacific. During 1972 and early 1973, the stratospheric inventory in each hemisphere again decreased. After mid-1973 the inventory rose after an atmospheric test in the northern hemisphere.

45. The annual deposition of ^{90}Sr in the northern and southern hemispheres is shown in table 2 for the period 1958-1975, in addition to the cumulative deposit in each hemisphere (89). (Deposition is the activity deposited on a specified area. The cumulative deposit is the activity present in a specified area at a given time; it is the result of past depositions and radioactive decay.) Between 1970 and 1973, deposition in both hemispheres fell off sharply, and the 1973 values were the smallest recorded since these measurements began. In 1974, however, there was an increase in the annual deposition in the northern hemisphere.

TABLE 2. ANNUAL DEPOSITION AND CUMULATIVE DEPOSIT OF ^{90}Sr

(MCi)

	Deposition			*Cumulative deposit*		
Year	*Northern hemisphere*	*Southern hemisphere*	*Global*	*Northern hemisphere*	*Southern hemisphere*	*Global*
Pre-1958	1.80[a]	0.65[a]	2.45[a]	1.70	0.60	2.30
1958	0.63	0.25	0.88	2.28	0.84	3.12
1959	1.05	0.18	1.23	3.26	1.00	4.26
1960	0.26	0.17	0.43	3.44	1.14	4.58
1961	0.35	0.17	0.52	3.70	1.29	4.99
1962	1.44	0.26	1.70	5.04	1.51	6.55
1963	2.62	0.31	2.93	7.51	1.78	9.29
1964	1.66	0.42	2.08	8.96	2.16	11.12
1965	0.77	0.36	1.13	9.50	2.46	11.96
1966	0.33	0.21	0.54	9.59	2.60	12.19
1967	0.17	0.11	0.28	9.52	2.65	12.17
1968	0.20	0.10	0.30	9.48	2.68	12.16
1969	0.15	0.14	0.29	9.40	2.76	12.16
1970	0.21	0.13	0.34	9.37	2.82	12.19
1971	0.19	0.15	0.34	9.33	2.90	12.23
1972	0.09	0.10	0.19	9.18	2.92	12.10
1973	0.03	0.03	0.06	8.98	2.88	11.86
1974	0.12	0.04	0.16	8.89	2.85	11.74
1975	0.06	0.03	0.09	8.73	2.81	11.54
Integrated deposition	12.13	3.81	15.94			
Stratospheric inventory	0.03	0.03[b]	0.06			
Total injection to January 1976	12.16	3.84	16.00			

Sources: References 89, 149.

[a] Estimated from the cumulative deposit, assuming a two-year decay.

[b] Assumed to be the same as for the northern hemisphere.

46. The deposition density of ^{90}Sr is measured monthly at a considerable number of monitoring stations in both hemispheres. (Deposition density is the activity deposited per unit area.) Estimates of the average integrated deposition density (the addition of all previous deposition densities in a location, without taking account of radioactive decay) of ^{90}Sr in each latitude band are shown in table 3 (89), together with the zonal populations and areas. This latitudinal distribution is useful for determining the dose commitment to the world population and in addition serves indirectly as a guide to the geographical distribution of other radionuclides released by atmospheric tests. It can be seen from table 3 that the integrated deposition density is maximum in the mid-latitude regions of each hemisphere.

47. The population-weighted deposition density is determined as follows: If N_i is the population of latitude band i and F_i is the average integrated deposition density of ^{90}Sr in that band, then the population-weighted

TABLE 3. LATITUDINAL DISTRIBUTION OF ^{90}Sr INTEGRATED DEPOSITION DENSITY

Latitude band	*Area of band (10^6 km^2)*	*Relative population of band (%)*	*Integrated deposition density of ^{90}Sr (mCi km^{-2})*
70°-80° N	11.6	0.0	19.1
60°-70° N	18.9	0.4	45.7
50°-60° N	25.6	12.2	79.2
40°-50° N	31.5	13.8	85.1
30°-40° N	36.4	18.2	62.4
20°-30° N	40.2	29.2	45.7
10°-20° N	42.8	9.8	30.0
0°-10° N	44.1	5.6	20.7
0°-10° S	44.1	5.8	18.9
10°-20° S	42.8	1.8	10.1
20°-30° S	40.2	1.6	18.0
30°-40° S	36.4	1.4	20.7
40°-50° S	31.5	0.1	24.5
50°-60° S	25.6	0.05	14.7

Sources: References 89, 155.

TABLE 4. STRONTIUM-90 AND CAESIUM-137 IN MILK

Country or area	$^{90}Sr/Ca$ quotient (pCi $(gCa)^{-1}$)										^{137}Cs concentration (pCi l^{-1})										Reference
	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	
Northern hemisphere																					
Austria	23	14	13	12							70	3	28	27							57, 58, 59
Belgium	13	9	8	9	6	6	5				36	17	20	15	10	13	10				72, 73
Canada	13	10	8	9	9	8	7				51	33	25	20	21	22	16				78, 79, 162, 205, 237, 253
Colombia	2	2	1		1	1	1	1													206, 207
Czechoslovakia	12																				183
Denmark	9	8	7	6	8	7	5	4	4	4	22	14	12	13	10	11	7	4	4	4	2
Egypt	13		6																		157, 158
Faroe Islands	73	51	45	37	37	34	25	23	20	19	800	586	507	463	357	352	268	251	254	198	3
Finland	13	10	9	8	7	7	6	5	5		134	92	70	54	49	44	36	30	28	25	64, 218
France (1)	19	14	12	9	8	9	8	6	6	6		21	20	19	21	22	15	8	6	8	96, 198, 222
France (2)	18	15	12	12	12	11	10	7	6	6	62	34	24	24	26	28	20	13	10	12	76
French Guiana	13	17			8	7	11	6			61	12			72	67	68				206, 207
Germany, Fed. Rep. of	16	11	9	9	8	8	7	6	6	5	61	35	27	25	31	29	25	18	20	15	52, 56
Guadeloupe		2	2	2	3	4	4	3					14		14	17	12	7			222, 253
India (Bombay)	5	3	3	2	3	2					11	6	5	5	4	4					146, 147, 170, 171
Israel	2	2																			90
Italy	13	10	8	8	7									34	25						74, 75
Jamaica	9	7	4	4	4	4	3				200	184	109	95	81	80	45				253
Japan	11	8	7	5	5	6	4	4	4	3	52	30	28	18	16	15	19	12	10	9	7, 253
Martinique		7	8	5	5	4	7	4				41	41		61	59	98	65			222, 253
Netherlands	15	9	8	7	6	5	5				43	37	28	23	17	16	10				72, 161, 168, 169
Norway	30	18	13	11	11	9	8	9	7		244	181	146	128	117	84	80	72	59	49	131
Panama	4										21	22	11	11							247
Poland	13	14	10	9	6	8	6	6	6	5	58	42	37	31	31	32	26	18	22	22	138
Puerto Rico	6	4	4	4							21	14									247
Republic of Korea	22	11	15																		143
Senegal	13	9	6		3	6	4														206
Sweden	15	10	8	7	7	7	6	5	5		63	38	30	20	23	26	18	11	11	10	106-108, 109, 228-230
Switzerland	15	9	7	7	8	9	7	5	5		29	16	15	14	15	16	12	7	11		129, 130
USSR	12	10	9	8	7	7	6	5			56	38	30	20	23	27	21	18			144, 257, 258, 261, 263, 264
United Kingdom	12	9	8	7	6	6	5	4	3	3	46	20	16	14	17	18	13	8	9	7	5, 50, 51, 178
United States	12	9									29	16									247
Alaska	12	6	6	5							34	20	13								247
Chicago	9	8	8	6									14	16	14	14	7	5			47, 125, 247
Hawaii	4	3	4	2							25	9									247
New York City	12	10	9	9	9	9	6	5	5	5											36, 112
Tampa	11	11	7	5	5	4	4				139	102	66	55	51	43	35	27			247, 253
Venezuela	4										14	9									247
Southern hemisphere																					
Argentina	5	5	4	4	3	4	4	3	2	2	24	21	19	20	20	19	17	13	12	5	21, 70, 71
Australia	7	5	4	5	6	7	5	4	4	4	28	20	15	18	19	21	18	11	7	6	9-11, 44, 91, 92, 99
Bolivia					1	1	1	1	1												76, 206
Chile	2	2	1		2	2	1	3	2						8	9					76, 69, 206, 207
Ecuador	5	2	1		1	1	1	1													76, 206, 207
Madagascar	2	2	1		2		1	1													76, 206, 207
New Caledonia	3	2	3		3	3	3	2	2		8	7	5		12	6	3	2			76, 206, 207
New Zealand	8	6	5	7	7	7	6	4			55	43	32	40	35	32	27	18	14		187-188
Peru	2	1	2																		206
Réunion		4	3	3	5	5	5	3	3			17	15	18	16	14	14	10			207, 222
Society Islands (Tahiti)	6	4	2		4	6	5	4	4		18	96	35		134	144	138	114	106		76, 206, 207

deposition density $\bar{F}$ is given by $\bar{F} = \Sigma_i F_i N_i / \Sigma_i N_i$. The population-weighted integrated deposition densities of ^{90}Sr from all tests for the northern hemisphere, for the southern hemisphere and for the whole world are 56.5, 17.6 and 52.3 mCi km^{-2}, respectively.

2. Strontium-90 in the environment

48. The deposition of ^{90}Sr occurs over land and water, but that over land is the more important pathway for human exposure. The quantitative aspects of the transfer of ^{90}Sr along terrestrial pathways are treated in detail in the following sections of this Annex.

49. Previous reports of the Committee have discussed the behaviour of ^{90}Sr in soils (244, 245). Recent measurements of the soil profile (114) have shown that ^{90}Sr is still present mostly in the upper layers, with 50 per cent in the first 4 cm and practically all in the top 30 cm. Only small amounts of ^{90}Sr are leached out of the soil and conveyed into fresh-water rivers and lakes. Concentrations in drinking waters are normally at least an order of magnitude lower than those found in other foodstuffs. Plants take up ^{90}Sr from soil through their root system. This root uptake and the time constants describing how ^{90}Sr becomes unavailable for plants are discussed in paragraphs 55 to 66.

50. Most of the ^{90}Sr fallout into the oceans is still present in the well mixed layer above the thermocline. Noshkin and Bowen (193), from measurements in the north and south Atlantic oceans, estimated that only about 1 per cent of the ^{90}Sr has reached the bottom sediments. In the open ocean, activity concentrations are about 0.2 pCi l^{-1} in the surface layer and smaller by a factor of at least 30 below the thermocline. In coastal areas and estuaries concentrations may be a factor of 5 higher.

51. Strontium-90 is taken up by marine biota, and becomes incorporated into the marine food chain. A number of determinations of the concentration factors have been performed in recent years for various marine biota by measurements of stable and radioactive strontium under laboratory and field conditions (63, 93, 191, 214, 240). Typical values are 100 for algae, 2-10 for crabs and lobster and about 1 for the muscle meat of fish. The amount in fish does not contribute greatly to the intake of ^{90}Sr by man. It is estimated that only about 3 per cent of the ^{90}Sr intake by man in Japan between 1966 and 1971 came from fish (240).

3. Levels in food

52. The annual average $^{90}Sr/Ca$ quotients in milk and in the whole diet from 1966 onwards are shown in tables 4 and 6. Values for earlier years are given in earlier reports of the Committee. Typically, levels in milk fell by about 30 per cent between 1970 and 1974. Data so far available indicate that levels in 1975 are about the same as those reported in 1974. Table 5 gives the annual average $^{90}Sr/Ca$ quotients in milk of some countries of the north temperate zone for the period 1955-1975. The numbers in the right-hand column of table 5 are the averages of the available data for each year. It can be seen that this average in 1975 is about 20 per cent of that prevailing during the peak years of 1963 and 1964.

TABLE 5. ANNUAL AVERAGE $^{90}Sr/Ca$ QUOTIENT IN MILK BY COUNTRY OR AREA
North temperate zone, 1955-1975
(pCi (gCa)$^{-1}$)

											United States				
Year	*Belgium*	*Canada*	*Denmark*	*Finland*	*France*	*Germany, Fed. Rep. of*	*Netherlands*	*Switzerland (eastern)*	*USSR (Moscow)*	*United Kingdom*	*Entire country*	*Chicago*	*New York City*	*Salt Lake City*	*Mean*
1955						3				4					3.5
1956						4				6					5.0
1957						8				6			5	4	5.3
1958						6				7		7	8	4	6.2
1959			9			8			8	10		7	11	6	8.6
1960			5	7		6			6	6		8	8	6	6.6
1961			4	6		6			4	6	7	6	7	4	5.6
1962			10	13		10	9		13	12	11	9	12	8	10.8
1963		26	24	22		27	25	27	23	26	19	17	26	19	23.3
1964		28	25	23		28	22	27	18	28	19	16	23	23	23.3
1965		19	17	18	24	21	17	23	14	19	14	12	19	17	18.2
1966	13	13	9	13	19	16	15	15	15	12	11	9	12	10	13.0
1967	9	10	8	10	14	11	9	9	8	9	9	8	10	5	9.2
1968	8	8	7	9	12	9	8	7	5	8		8	9		8.5
1969	9	9	6	8	9	9	7	7	5	7		6	9		7.8
1970	6	9	8	7	8	8	6	8	7	6			8		7.2
1971	6	8	7	7	9	8	5	9	7	6			8		7.2
1972	5	7	5	6	8	7	5	7	6	5			6		6.2
1973			4	5	6	6		5	5	4			5		5.2
1974			4	5	6	6		5		3			5		5.0
1975			4			5				3			5		4.3

TABLE 6. STRONTIUM-90 AND CAESIUM-137 IN TOTAL DIET

Country or area	$^{90}Sr/Ca$ quotient (pCi $(gCa)^{-1}$)										^{137}Cs daily intake (pCi)										Reference
	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	
Northern hemisphere																					
Austria	25	15	15	14							135	53	60	51							59
Denmark	14	10	8	8	7	8	8	6	7	6	79	44	39	38	32	38	31	15	18	18	2
Egypt	45		13																		157, 158
Faroe Islands	33	22	23	17	20	15	13	12	10	10	496	480	502	403	384	202	191	316	239	281	3
Finland	21										260										132
France (1)	22	19	17	15	15	14	13	10	11	9											76
France (2)			21	20	18	18	16	13	12	12			38	34	37	37	31	15	16	14	96, 198, 222
Germany, Fed. Rep. of	26	18	15	14	11	13	11	9	11	8	123	77	40	36	28	53	27	18	17	16	52, 54
Greenland	15	9	7	8	6	8	9	6	5	6	89	297	346	61	137	51	55	71	54	29	4
India	12	28	10								6				3	20					145, 172
Japan (urban)	24	18	19	21	15	12		12	9	9	20	14	13	14	9	8		7	10	7	8, 174
Netherlands	20	14	12	11	9	8	8				90	50	32	28	24	22	14				168, 169
Norway	38										420										132
Sweden	22										132	88	71	65	58	50					132, 156, 233
USSR (urban)	41	30	27	21	23	23	21	19			145	93	56	38	38	47	34	29			45, 257, 261, 262, 263
United States																					
Country average	16	12									55	30	34	28	25	24	17	11			47, 104, 125, 247
Alaska	29	26																			247
Hawaii	10	6									65	35									247
New York City	17	16	14	12	12	13	11	10	9	8											30, 36
San Francisco	6	6	4	4	4	4	4	3	3	3											30, 36
Southern hemisphere																					
Argentina	7	7	5	6	5	5	5	4	3	3		24	19	18	17	17	15	13	11	4	21, 70, 71
Australia	7	6	5	5	6	7	6	5	4	4											9, 11, 91, 92, 99, 180

53. The annual values of the ratio of the $^{90}Sr/Ca$ quotient in the total diet to that in milk are shown in table 7. Bennett (30, 36) has investigated the relative contributions that different foods make to the ^{90}Sr intake in New York and San Francisco. The results for New York are shown in figure VI, which presents the $^{90}Sr/Ca$ quotient in various components of the diet. Aarkrog and Lippert (2) have reported similar results for the Danish diet, some of which are plotted in figure VII. When expressed as $^{90}Sr/Ca$ quotients, the peak values recorded for fruit, vegetables and grain products are about 50 pCi $(gCa)^{-1}$, for milk products they are about 50 per cent of that, for meat, fish and eggs, only about 20 per cent. It is also notable that the $^{90}Sr/Ca$ quotient in milk products and meat reaches a peak during periods of high fallout rate and then decreases rapidly over the next 5-8 y, while for fruit and vegetables it remains higher for longer periods of time. It is expected, therefore, that the long-term variation of the ^{90}Sr intake with time would depend on the composition of the diet.

TABLE 7. RATIO OF THE $^{90}Sr/Ca$ QUOTIENT IN THE TOTAL DIET TO THAT IN MILK

Country	*1963*	*1964*	*1965*	*1966*	*1967*	*1968*	*1969*	*1970*	*1971*	*1972*	*1973*	*1974*	*1975*	*Mean for 1963-1975*
Argentina	1.8	1.5	1.3	1.4	1.4	1.3	1.5	1.3	1.3	1.3	1.3	1.5	1.3	1.4
Australia	1.1	1.0	0.9	1.0	1.2	1.3	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.1
Denmark	1.3	2.0	1.6	1.5	1.3	1.2	1.4	0.9	1.2	1.6	1.7	1.8		1.5
Finland			1.8	1.6										1.7
France				1.2	1.3	1.4	1.3	1.3	1.3	1.3	1.6	1.8	1.5	1.4
Germany, Federal Republic of	1.8	1.6	1.6	1.7	1.6	1.6	1.5	1.5	1.8	1.7	1.6	1.8	1.7	1.7
India (Bombay)[a]		1.7	2.9	2.1	6.9	2.7								3.3
Japan	2.1	2.2	2.3	2.2	2.3	2.7	4.2	3.0	3.1		3.2	2.6	3.0	2.7
Norway			1.3	1.4										1.3
Sweden			1.4	1.5										1.4
USSR	2.3	3.1	3.7	3.4	3.0	3.0	2.6	3.3						3.1
United Kingdom	0.9	0.9	1.0											0.9
United States														
Hawaii	1.6	2.2	3.5	2.5	2.0									2.4
New York City	1.1	1.3	1.2	1.4	1.6	1.6	1.3	1.5	1.6	1.8	1.9	1.9	1.6	1.5

[a] Since most of the wheat and rice is imported, the diet data do not reflect the local fallout levels.

54. Aarkrog and Lippert (2) have reported that the $^{90}Sr/Ca$ quotients in potatoes, cabbage and carrots grown in Denmark have not diminished greatly since 1963, whereas in milk it has fallen by a factor of five. On the other hand, Mukhin (182) has reported results on the ^{90}Sr concentrations of potatoes and cabbage grown in the Union of Soviet Socialist Republics, which have fallen by a factor of about five between 1963 and 1969. Borisov *et al.* (45) have reported that cereals have consistently been the major contributor of ^{90}Sr in the USSR diet; this would account for the fact that the $^{90}Sr/Ca$ quotient in total diet and also the ratio of total diet $^{90}Sr/Ca$ to that of milk is higher in the USSR than in other countries having high-milk diets.

4. Transfer of ^{90}Sr from fallout to diet

55. Transfers between two successive steps in the sequence linking input into the environment to the resulting dose commitment can be described by transfer factors, defined as the quotient of the infinite time-integrals of the quantities considered for each step (see Annex A). In the transfer model used by the Committee in the 1969 and 1972 reports (244, 245), which is outlined in paragraph 2 of this Annex, the transfer factor from fallout to diet is given by

$$P_{23} = \frac{\int_{-\infty}^{\infty} C(t)\,dt}{\int_{-\infty}^{\infty} f(t)\,dt} \qquad (1)$$

where $C(t)$ is the $^{90}Sr/Ca$ quotient in the diet at time t, and $f(t)$ is the deposition density rate of ^{90}Sr at time t.

56. If the values of $C(t)$ and $f(t)$ are assessed as averages for discrete intervals of time h, equation 1 becomes

$$P_{23} = \frac{\sum_{i=-\infty}^{\infty} hC(i)}{\sum_{i=-\infty}^{\infty} hf(i)} = \frac{\sum_{i=-\infty}^{\infty} C(i)}{\sum_{i=-\infty}^{\infty} f(i)} \qquad (2)$$

Equation 2 can be reformulated to take account of the determinations of the $^{90}Sr/Ca$ quotient in individual components of the diet. If the fractional contribution of component j of the diet to the total dietary calcium is W_j, and the $^{90}Sr/Ca$ quotient in that component is $C_j(i)$, then

$$P_{23} = \sum_j W_j \frac{\sum_{i=-\infty}^{\infty} C_j(i)}{\sum_{i=-\infty}^{\infty} f(i)} = \sum_j W_j P_{23}^j \qquad (3)$$

where P_{23}^j is the transfer factor from fallout to diet component j.

57. In the 1969 and 1972 reports of the Committee (244, 245), the $^{90}Sr/Ca$ quotient in a diet component was related to the past and present deposition density rate $f(\tau)$, by the expression

$$C_j(t) = \int_{-\infty}^{t} K_j(t-\tau) f(\tau)\,d\tau \qquad (4)$$

where K_j is a transfer function defined by this equation. If both $C_j(t)$ and $f(\tau)$ are given as averages over discrete

intervals of time of duration h, the time becomes $t = nh$, and equation 4 is equivalent to

$$C_j(nh) = \sum_{m=-\infty}^{n} hK_j(nh-mh)\,f(mh) = \sum_{l=0}^{\infty} hK_j(lh)\,f(nh-lh) \quad (5)$$

The transfer factor P_{23}^j can be obtained from the transfer function K_j by the relation

$$P_{23}^j = \sum_{l=0}^{\infty} hK_j(lh) \quad (6)$$

where, in practice, the time interval h is 1 y, because most of the determinations of ^{90}Sr in food have been reported on a calendar-year basis.

58. Several transfer functions between fallout and diet components have been tried in regression analyses of reported data. In the 1972 report of the Committee (245) the following function was used:

$$C_j(i) = h_1^j f(i) + h_2^j f(i-1) + h_3^j \sum_{m=1}^{\infty} e^{-\mu m} f(i-m) \quad (7)$$

In this equation, $f(i)$ is the annual deposition density in the year considered, $f(i\text{-}1)$ is the annual deposition density in the previous year, and the summation is carried out over the deposition of all preceding years, each weighted by an exponential term describing the combined physical decay of ^{90}Sr and any decrease in the availability to plants of ^{90}Sr in soil. The factors b_1^j, b_2^j and b_3^j, and the effective mean life of available ^{90}Sr, μ^{-1}, can be derived from reported data by regression analysis.

59. In the past, this transfer function was found to be adequate for predicting ^{90}Sr/Ca quotients in milk. By allowing each of the parameters b_1, b_2, b_3 and μ to vary in a regression analysis, Bennett (30, 36) has fitted equation 7 to five New York City diet components (milk products; cereals; meat, fish and eggs; fruit; and vegetables) and also to the same five components of the Danish diet (22). The results are shown in the continuous curves in figures VI and VII for New York and Denmark respectively. The factors obtained from this regression analysis are shown in tables 8 and 9 (22). The estimated transfer coefficients for each individual diet component P_{23}^j in the two sets of Danish data are in reasonably good agreement with each other, especially taking into account that the definitions of the components are not the same in the two cases. Also shown in these two tables are values of P_{23} for the total diet, estimated from a regression analysis with the total composite diet data. The 95% confidence limits on P_{23} are 4.3 and 6.4 pCi y (gCa)$^{-1}$ per mCi km^{-2}.

TABLE 8. PARAMETERS OF THE TRANSFER FUNCTION BETWEEN ^{90}Sr FALLOUT AND DIET

Obtained by regression analysis from New York City data

Parameter[a]	*Milk products*	*Grain products*	*Meat, fish, eggs*	*Vege-tables*	*Fruit*	*Total composite diet*
b_1	0.69	0.86	0.004	0.96	1.36	0.90
b_2	0.21	1.91	0.17	0.37	0.00	0.54
b_3	0.20	0.30	0.31	1.03	0.90	0.36
μ	0.14	0.13	0.28	0.07	0.03	0.10
P_{23}^j	2.23	4.92	1.13	15.45	30.46	4.87
W_j	0.582	0.179	0.111	0.089	0.039	1.0
$W_jP_{23}^j$	1.30	0.88	0.13	1.38	1.19	4.87
Total diet P_{23}			4.88			4.87

[a]The unit for parameters b_1, b_2, b_3, is pCi (gCa)$^{-1}$ per mCi km^{-2}. The unit for parameter μ is y^{-1}. The unit for the transfer factor P_{23}^j is pCi y (gCa)$^{-1}$ per mCi km^{-2}. W_j is the fractional contribution of component j to the total Ca diet.

TABLE 9. PARAMETERS OF THE TRANSFER FUNCTION BETWEEN ^{90}Sr FALLOUT AND DIET

Obtained by regression analysis from Danish data

Parameter[a]	*Milk products*	*Grain products*	*Meat, fish, eggs*	*Vege-tables*	*Fruit*	*Total composite diet*
b_1	0.98	0.98	1.90	2.37	10.04	1.07
b_2	0.46	2.49	0.45	0.00	0.50	1.22
b_3	0.23	0.02	0.28	0.90	0.45	0.19
μ	0.13	0.02	0.12	0.06	0.02	0.10
P_{23}^j	3.12	4.34	4.61	16.50	32.59	4.01
W_j	0.44	0.48	0.02	0.05	0.01	1.00
$W_jP_{23}^j$	1.37	2.08	0.09	0.83	0.33	4.01
Total diet P_{23}			4.70			4.01

[a]The unit for parameters b_1, b_2, b_3, is pCi (gCa)$^{-1}$ per mCi km^{-2}. The unit for parameter μ is y^{-1}. The unit for the transfer factor P_{23}^j is pCi y (gCa)$^{-1}$ per mCi km^{-2}. W_j is the fractional contribution of component j to the total Ca diet.

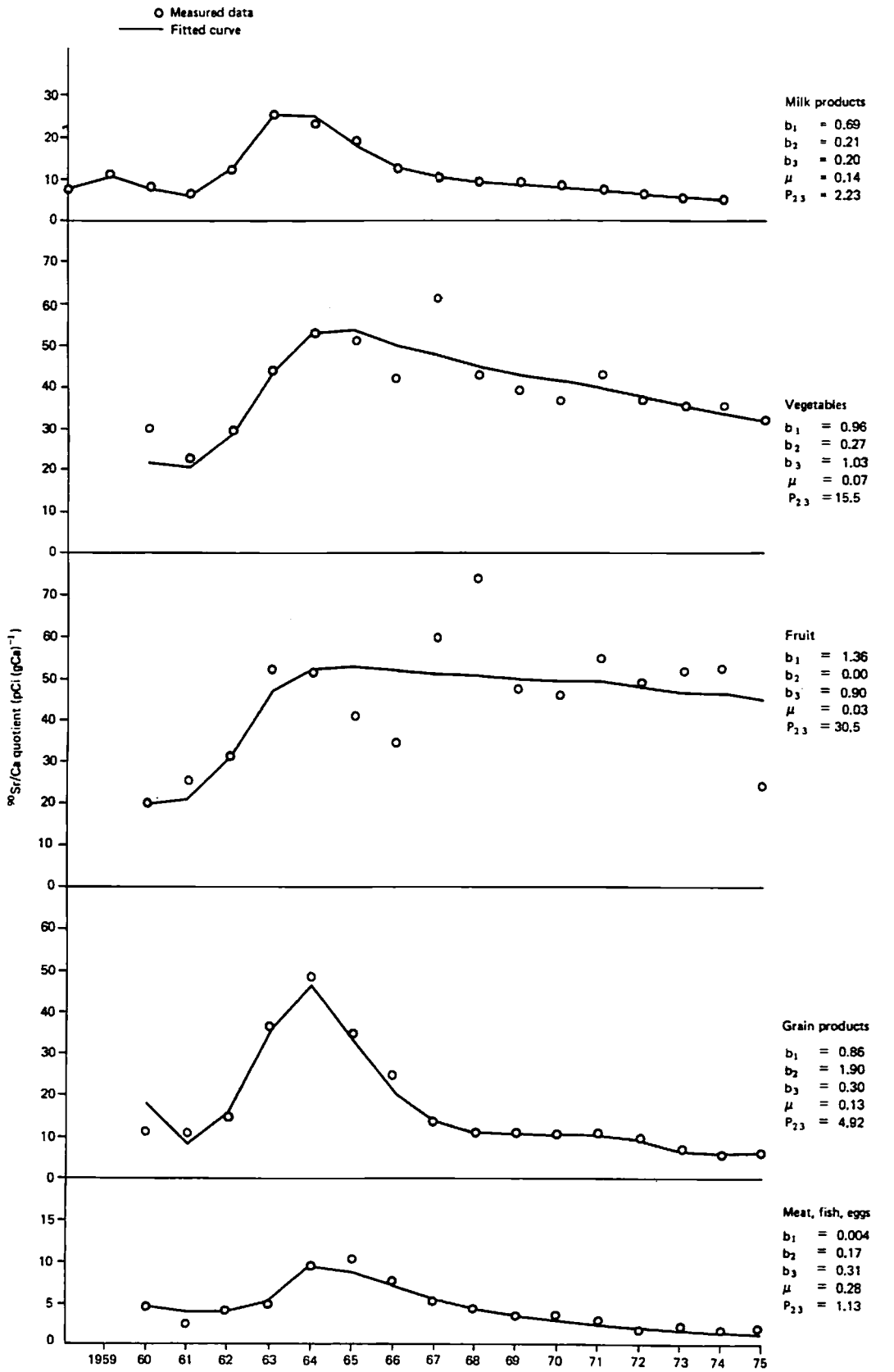


Figure VI. Variation of ^{90}Sr in various diet components in New York City, 1959-1975. The unit for the parameters b_1, b_2, b_3 is pCi $(gCa)^{-1}$ per mCi km^{-2}. The unit for parameter μ is y^{-1}. The unit for the transfer factor P_{23} is pCi y $(gCa)^{-1}$ per km^{-2}.

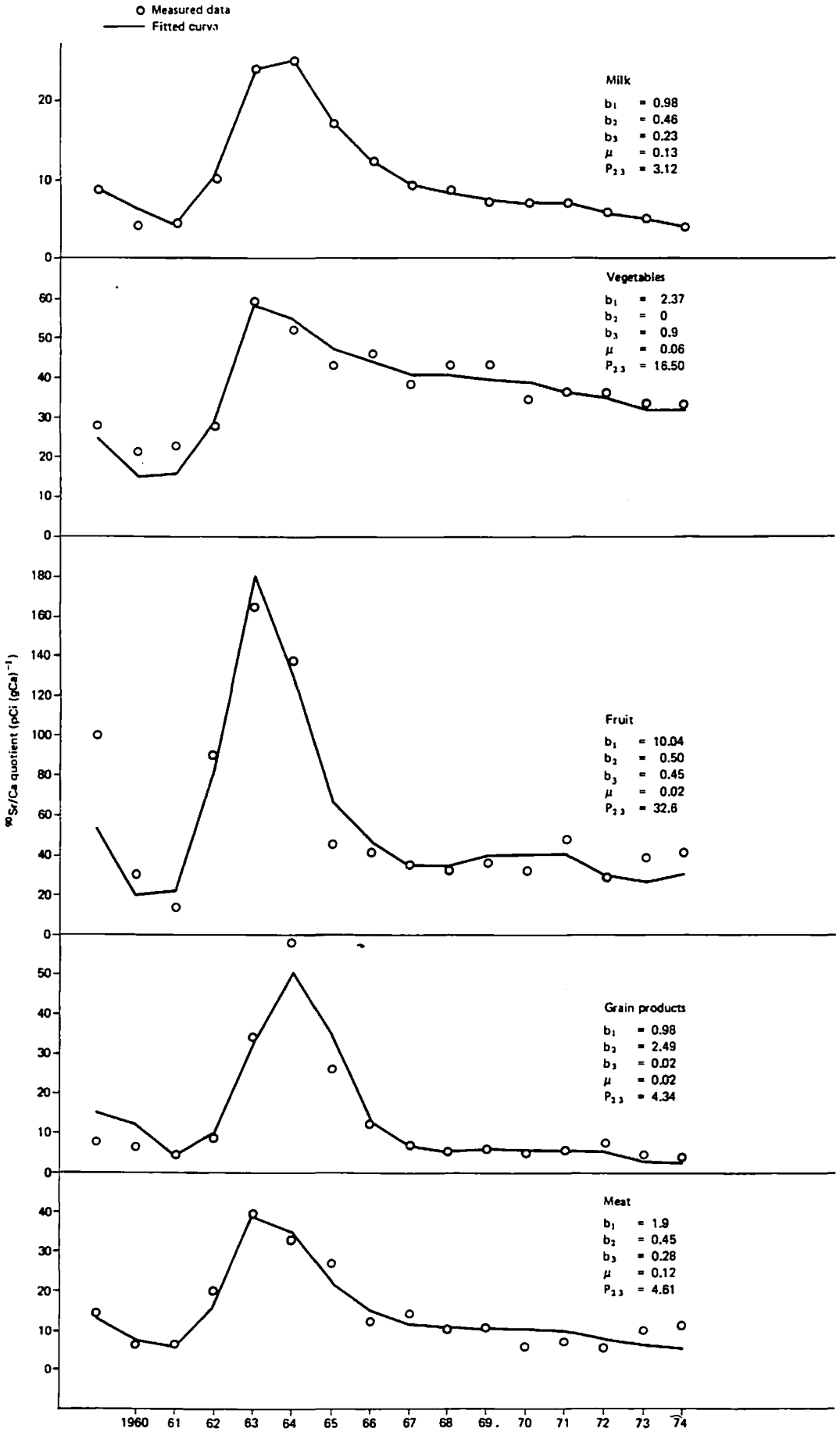


Figure VII. Variation of ^{90}Sr in various diet components in Denmark, 1960-1974. The unit for the parameters b_1, b_2, b_3 is pCi (gCa)$^{-1}$ per mCi km^{-2}. The unit for parameter μ is y^{-1}. The unit for the transfer factor P_{23} is pCi y (gCa)$^{-1}$ per mCi km^{-2}.

60. The total diet transfer coefficient P_{23} is given in terms of the transfer factor for each component in equation 3. The contribution from component j is $W_j P_{23}^j$, where W_j is the fractional contribution of component j to the total dietary calcium intake. To compare the relative contribution of different diet components to the ^{90}Sr intake, it is necessary to compare the products $W_j P_{23}^j$, which are also given in tables 8 and 9. The values of the total diet transfer factor P_{23} estimated from the different dietary components using equation 3 agree with those estimated from the composite total diet, both for New York and for Denmark. Milk products appear to contribute about 30 per cent P_{23} in both places. Meat, fish and eggs contribute only to a small extent. In Denmark grain products contribute about 45 per cent of the intake, in New York, only about 17 per cent. Fruit and vegetables contribute about 54 per cent of ^{90}Sr intake in New York, but only 24 per cent in Denmark.

61. These differences reflect not only different annual intakes for each foodstuff, but also different agricultural practices and soil conditions. In general, it may be said that ^{90}Sr in the diet comes mainly from milk products, grain products, fruit and vegetables. Most of the ^{90}Sr from grain products is received during the years of heavier fallout; in the case of milk about 40 per cent is received during the years of fallout and the rest over some 8 y afterwards. For fruit and vegetables, most of the contribution seems to be delivered over a period of 12-14 y after deposition. This pattern is consistent with observations in the Federal Republic of Germany, where lettuce, cabbage, citrus fruits and potatoes showed little change in activity concentration between 1963 and 1967 (53).

62. A similar analysis of the reported ^{90}Sr data for the individual components of the Argentine and Australian diets has been carried out (22). Since the deposition density rate of ^{90}Sr did not peak so sharply in the southern hemisphere, the estimates of parameters obtained by fitting the dietary ^{90}Sr data are probably less precise. However, differences are evident when these values are compared with the comparable ones derived from the New York and Danish data. For Argentina, the values obtained for P_{23} were (unit: pCi y (gCa)$^{-1}$ per mCi km^{-2}): 6.49 for the composite diet, 6.00 from analysis of separate dietary components. The greatest contribution came from cereals and milk products. For Australia, a value of 7.47 was obtained from the composite diet and 10.7 from an analysis of individual dietary components. The greatest contribution also came from cereals and milk products.

63. From the above analysis of diets in two countries in the southern hemisphere it appears that the transfer factors between fallout and diet are about twice as great as those for countries in the northern hemisphere with similar diets. That is consistent with the observation that concentrations of ^{90}Sr in human bone from these southern latitudes are not substantially lower than those at similar latitudes in the northern hemisphere, even though the integrated deposition density of ^{90}Sr has been only about one fourth of that in the northern hemisphere.

64. There are as yet insufficient data to predict what contribution fruit and vegetables will make to the transfer factors for diets with little or no milk products. There is also the possibility, as suggested by Borisov *et al.* (45), that the strontium and calcium present in different components of the diet are not equally available.

65. Equation 7 has been fitted by regression analysis to the milk and fallout ^{90}Sr data from several regions in the world. The resulting parameters are shown in table 10, and the fitted and measured ^{90}Sr levels in milk are shown in figure VIII for the Faroe Islands, Norway and San Francisco (22). The fallout-to-milk transfer factor, P_{23}^{milk}, for the Faroe Islands is about twice as large as in other countries.

TABLE 10. PARAMETERS OF THE TRANSFER FUNCTION FROM ^{90}Sr FALLOUT TO MILK

Obtained by regression analysis of data for various countries and areas

Parameter[a]	Argentina	Australia	Denmark	Faroe Islands	Norway	San Francisco	United Kingdom	United States	Northern hemisphere
b_1	1.36	1.69	0.98	2.72	0.70	0.61	0.89	0.87	0.87
b_2	0.85	1.18	0.46	1.28	0.44	0.61	0.47	0.23	0.45
b_3	0.22	0.43	0.23	0.90	1.02	0.19	0.15	0.31	0.23
μ	0.16	0.09	0.13	0.23	0.33	0.19	0.13	0.20	0.12
P_{23}^{milk}	3.43	7.44	3.12	7.48	3.74	2.13	2.44	2.50	3.13

[a] The unit for parameters b_1, b_2, b_3 is pCi (gCa)$^{-1}$ per mCi km^{-2}. The unit for parameter μ is y^{-1}. The unit for the transfer factor P_{23}^{milk} is pCi y (gCa)$^{-1}$ per mCi km^{-2}.

66. A representative value of P_{23} for dose commitment calculations can be derived from regression analysis of fallout and total diet data. However, only for a few localities is this combined information available for sufficiently long periods. The average of the values of P_{23} found with this procedure with the data from Argentina, Australia, Denmark and New York, is 5.7 pCi y (gCa)$^{-1}$ per mCi km^{-2}. As already discussed, P_{23} can also be assessed by estimating first the $P_2^j{}_3$ and then applying equation 3. The average of the values for Denmark and New York, estimated by this procedure, is 4.8 pCi y (gCa)$^{-1}$ per mCi km^{-2}. It should be noted that both estimated values of P_{23} apply to areas of high-milk diets.

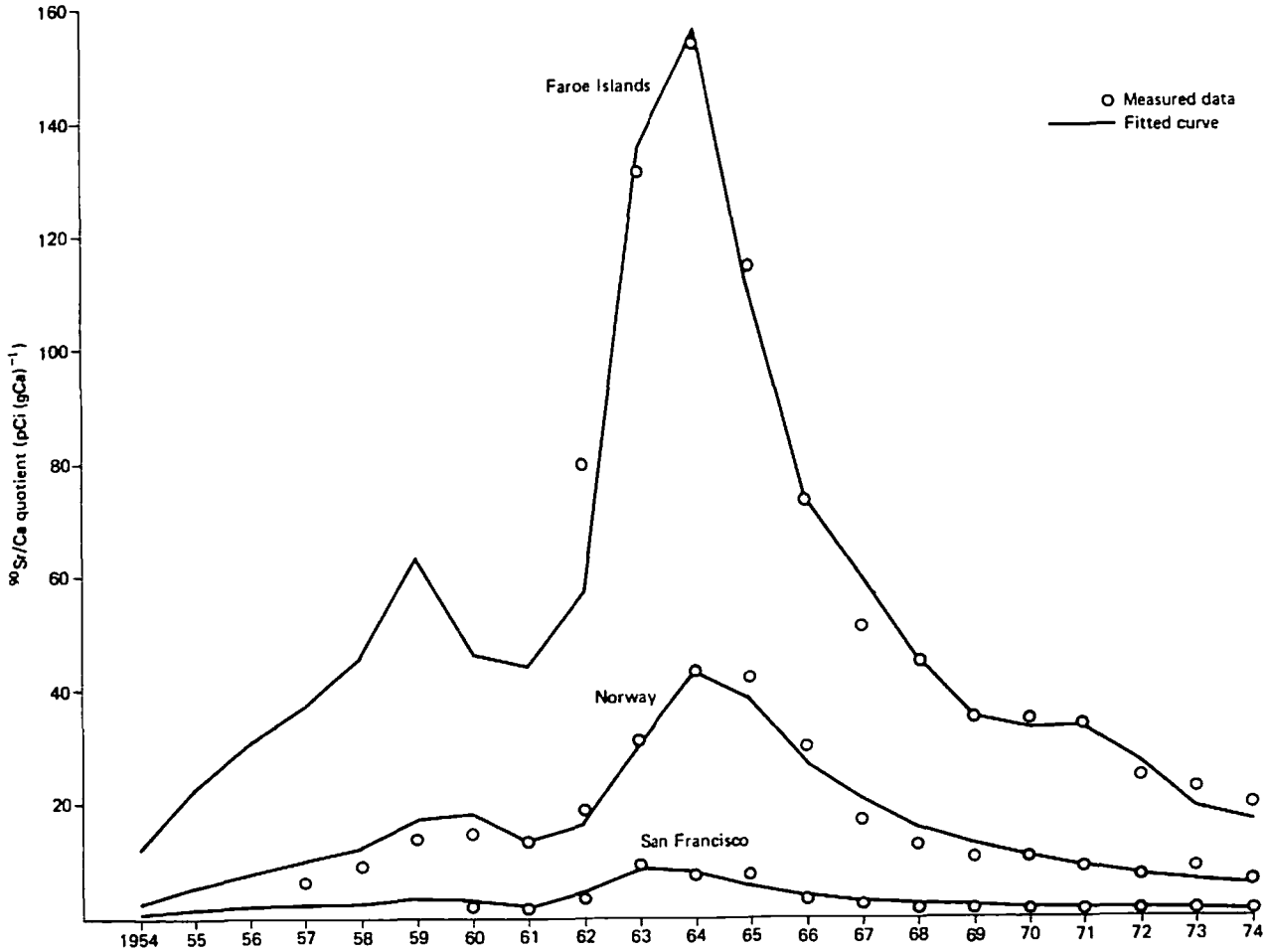


Figure VIII. Variation of ^{90}Sr in milk in the Faroe Islands, Norway and San Francisco, 1954-1974 (22)

67. A less direct procedure for estimating the value of P_{23} is to assess P_{23}^{milk} by regression analysis and then multiply this value by the ratio of the ^{90}Sr/Ca quotient in total diet to that in milk. This procedure is more uncertain because it requires the assumption that the diet-to-milk ratio would remain unchanged at the value observed in the past. On the other hand, the procedure makes it possible to estimate P_{23} for more regions, because of the availability of long series of milk measurements. The range of the values of P_{23}^{milk} given in table 10, in pCi y (gCa)$^{-1}$ per mCi km^{-2}, is 2.1-7.4, with an average of 3.3. This value, multiplied by an estimated average diet-to-milk ratio of 1.4, gives a value of 4.6 for the P_{23} factor in areas of high-milk diet.

68. Estimates of P_{23} are strongly dependent on the value of μ, the inverse of the effective mean life of available ^{90}Sr. The effect of this parameter is exemplified by calculations of P_{23} using the average values of b_1, b_2 and b_3 of table 10 and a diet-to-milk ratio of 1.4, and with μ varying over the range defined by the highest value of table 10 (0.33 y^{-1}) and the value used in the 1966 and 1969 reports of the Committee (243, 244), which most probably is an underestimate (0.05 y^{-1}). These calculations give values of P_{23} in the range of 3-10 pCi y (gCa)$^{-1}$ per mCi km^{-2}. As noted in paragraph 59, the 95% confidence limits on the estimated value of P_{23} for the New York diet are 4.3 and 6.4 pCi y (gCa)$^{-1}$ per mCi km^{-2}.

69. For the purpose of assessing dose commitments from ^{90}Sr for the world population a value for P_{23} of 5 pCi y (gCa)$^{-1}$ per mCi km^{-2} is used in this report. This value gives adequate representation of areas of high-milk diet in the northern hemisphere; but it underestimates P_{23} for at least some areas of high-milk diet in the southern hemisphere. It could also underestimate P_{23} for other diets, including those for which there are no direct assessments. From the diet-to-milk ratios of table 7, weighted by the sizes of the populations with high-milk diets and low-milk diets, it can be shown that the above value for P_{23} could lead to underestimates of the dose commitment by a factor not exceeding two for populations with low-milk diets.

5. Strontium-90 levels in bone

70. New data on the ^{90}Sr/Ca quotient in bone are shown in table 11. Only a few data are available for 1974 and 1975, but in general they are slightly less than those observed in 1971-1972. Table 12 gives the ^{90}Sr/Ca quotients in adult vertebrae for some countries in the northern hemisphere from 1962 to 1974. For the most part the differences in the results are small, the values for adult vertebrae lying between 1 and 2 pCi (gCa)$^{-1}$. The values for Nepal and Norway seem to be significantly higher than the others.

TABLE 11. STRONTIUM-90/Ca QUOTIENT IN HUMAN BONE BY COUNTRY AND AGE

(The number in parentheses is the number of samples)

(pCi (gCa)$^{-1}$)

Country	Year	Age (y)								Adult bone type[a]	Reference
		Newborn or stillborn	< 1	1	2	3	4	5-19	> 19		
					Northern hemisphere						
Canada	1968	3.2 (8)	4.1 (86)	4.8 (17)	4.3 (16)	4.4 (12)	5.8 (4)	3.8 (59)	2.7 (38)	V	
	1969	2.5 (6)	4.0 (47)	5.0 (5)	5.1 (5)	4.4 (4)	4.2 (8)	3.3 (48)	2.2 (37)	V	
Czechoslovakia	1966	2.2 (30)	3.3 (63)	3.5 (9)	3.3 (8)	3.8 (11)	3.0 (5)	2.9 (59)	1.8 (103)	V	245
	1967	1.6 (31)	2.8 (91)	4.1 (20)	3.8 (12)	2.9 (12)	2.9 (9)	2.8 (63)	1.9 (122)	V	
	1968								1.7 (54)	V	
	1969			3.2 (23)	2.3 (9)	2.8 (10)	3.0 (10)	2.4 (59)	1.8 (62)	V	
	1970	1.2 (12)	2.2 (14)	2.7 (11)	3.8 (9)	3.1 (4)	2.8 (5)	2.6 (32)	1.8 (106)	V	48
	1971	1.0 (22)	1.9 (16)	2.2 (7)		1.7 (6)	1.3 (22)	2.0 (53)	1.5 (86)	V	
	1972								1.6 (54)	V	49
	1973								1.4 (43)	V	
Denmark	1969	1.2 (19)	1.7 (33)	2.4 (3)		2.1 (1)	1.8 (3)	1.9 (36)	1.3 (27)	V	245
	1970	0.9 (18)	1.9 (26)	1.9 (4)	1.9 (4)	1.7 (4)	0.8 (1)	1.5 (31)	1.3 (49)	V	
	1971	1.1 (5)	2.7 (14)	4.5 (1)	3.3 (2)	3.3 (1)	2.0 (6)	2.2 (40)	1.7 (36)	V	
	1972	1.9 (16)	2.4 (16)	2.2 (1)		3.1 (3)	1.4 (1)	1.8 (30)	1.6 (14)	V	
	1973	1.9 (5)	2.0 (3)	0.8 (5)	1.4 (5)	3.2 (6)		1.6 (38)	1.5 (71)	V	2
	1974	1.3 (3)			1.8 (38)			1.4 (39)	1.4 (104)	V	
	1975	1.3 (1)			2.0 (13)			1.5 (32)	1.5 (85)	V	
Egypt	1968								0.4 (7)	V	245
	1969							0.1 (8)	0.2 (14)	V	
Fiji	1974								1.0 (12)	V	121
France (1)	1967	1.9 (5)	3.7 (53)	5.3 (10)	5.0 (5)		4.0 (1)	3.5 (41)	2.2 (55)	V	
	1968	1.6 (60)	3.2 (102)	4.4 (13)	3.7 (9)	3.9 (4)	3.8 (6)	2.8 (38)	2.3 (88)	V	245
	1969	1.6 (25)	3.2 (87)	3.7 (15)	3.1 (12)	3.6 (5)	3.0 (6)	2.8 (54)	2.0 (105)	V	
	1970	1.6 (37)	2.7 (73)	2.9 (15)	2.6 (11)	3.2 (6)	2.3 (15)	2.1 (42)	1.9 (132)	V	139
	1971	1.6 (54)	2.4 (67)	2.9 (16)	2.1 (9)	2.6 (3)	3.8 (3)	2.3 (32)	1.8 (153)	V	76
	1972	1.2 (29)	2.1 (33)			2.1 (11)		2.0 (31)	1.6 (93)	V	
	1973	1.08 (23)	1.7 (36)			1.8 (18)		1.6 (10)	1.5 (109)	V	
France (2)	1967								1.7 (55)	R	245
	1968								1.0 (45)	R	
	1969								1.3 (61)	R	
	1970								1.2 (18)	R	

Country	Year	Age (y)								Adult bone type[a]	Reference
		Newborn or stillborn	< 1	1	2	3	4	5-19	> 19		
Federal Republic of Germany	1968	1.2 (159)	2.4 (25)			2.8 (17)		2.5 (34)	1.8 (64)	R, S, V	245
	1969	1.1 (98)	1.9 (14)			2.3 (10)		2.0 (21)	1.7 (40)		
	1970	1.0 (94)	1.6 (112)			2.0 (12)		1.8 (21)	1.7 (36)		55
	1971	1.0 (30)	1.3 (4)			2.1 (4)		1.9 (6)	1.6 (12)		
India	1973							0.9 (1)	0.9 (10)	V	122
	1975								2.3 (12)		120
Jamaica	1970								0.9 (21)	V	245
Japan	1967		3.9 (2)	3.8 (2)	3.3 (2)	2.5 (1)	2.1 (1)	2.5 (21)	0.4 (1)	C	
	1968	1.1 (12)	2.0 (31)	3.2 (10)	2.3 (4)	2.3 (3)	1.8 (3)	2.1 (47)	0.6 (13)	C	
	1969	0.7 (30)	1.5 (15)	2.1 (5)	2.6 (7)	1.5 (7)	0.6 (1)	1.4 (26)	0.7 (12)	C	
	1970	0.7 (23)			2.5 (1)		2.0 (3)	1.7 (14)	1.2 (6)	C	
	1971	0.8 (37)			1.8 (4)			1.2 (20)	1.3 (2)	C	234
	1972	0.8 (30)	2.1 (9)	2.9 (2)		2.0 (1)	1.1 (1)	1.3 (14)	1.2 (10)	V	235
	1973	0.7 (19)	1.3 (4)	1.5 (1)				1.3 (10)	1.2 (10)	V	
	1974							1.5 (10)	1.1 (24)	V	236
	1975	0.6 (29)						1.4 (5)	1.0 (22)	V	
Nepal	1974								3.0 (12)	V	
	1975	1.9 (2)				2.8 (1)		4.0 (8)	3.5 (30)	V	121
New Guinea	1974								0.5 (12)	V	
Norway	1969	2.6 (38)	3.5 (13)			4.5 (6)		4.7 (9)	3.4 (90)	V	
	1970	2.7 (48)	3.8 (15)			4.1 (7)		4.2 (19)	3.7 (84)	V	
	1971	2.9 (43)	3.4 (26)			3.7 (7)		3.6 (20)	3.3 (46)	V	68
	1972	2.8 (44)	3.1 (15)			4.0 (7)		3.5 (20)	3.5 (77)	V	
	1973	1.6 (55)	2.9 (17)			3.7 (14)		2.5 (20)	2.7 (33)	V	
	1974	1.7 (44)	2.8 (9)			3.2 (11)		2.9 (22)	2.4 (54)	V	67
	1975	1.5 (31)	2.6 (21)			2.1 (10)		2.4 (22)	2.8 (100)	V	100
Senegal	1969								1.0 (12)	V	
	1970								1.3 (24)	V	245
Switzerland	1970								2.5 (47)	V	
	1971								2.2 (26)	V	
	1972								2.4 (45)	V	129
Thailand	1970							0.9 (1)	0.7 (6)	V	
	1971							0.7 (1)	0.5 (5)	V	245
	1973							0.7 (1)	0.5 (10)	V	122

TABLE 11 *(continued)*

Country	Year	Age (y)								Adult bone type[a]	Reference
		Newborn or stillborn	< 1	1	2	3	4	5-19	> 19		
Uganda	1970								1.1 (23)	V	245
USSR[b]	1968	1.7 (81)	2.4 (19)			3.0 (13)		2.2 (224)	1.2 (694)	N	259
	1969	1.5 (103)	2.1 (30)			3.1 (12)		2.0 (288)	1.2 (1 142)	N	260
	1970	1.4 (81)	2.4 (32)			2.9 (35)		3.1 (329)	1.4 (1 249)	N	260
	1971	1.0 (55)	2.3 (7)			2.5 (8)		2.7 (162)	1.3 (867)	N	260
United Kingdom	1968	1.3 (101)	2.9 (27)	3.2 (9)	2.7 (7)	3.4 (4)	2.7 (5)	1.9 (73)	1.6 (34)	V	245
	1969	1.2 (16)	2.6 (46)	2.2 (4)	2.0 (6)	2.3 (10)	2.5 (3)	1.8 (45)	1.5 (32)	[c]	163
	1970	1.2 (21)	2.1 (56)	2.4 (6)	2.4 (9)	2.2 (4)	1.9 (10)	1.6 (38)	1.3 (18)	V	163
United States											
New York	1969		2.6 (23)	2.7 (1)	3.2 (2)	3.6 (1)	2.8 (2)	2.5 (29)	1.7 (25)	V	245
	1970		2.5 (12)	2.8 (1)		2.4 (1)		2.1 (20)	1.6 (52)	V	245
	1971		2.2 (8)	3.3 (1)	1.7 (2)	2.7 (2)	2.0 (3)	2.1 (36)	1.4 (56)	V	24
	1972		1.6 (8)	3.4 (2)	2.9 (1)	2.7 (1)	2.6 (3)	1.8 (33)	1.4 (107)	V	26
	1973		1.6 (15)	3.3 (1)	1.4 (1)	1.9 (1)		1.5 (23)	1.3 (54)	V	31
	1974		1.7 (7)	1.6 (2)	1.6 (1)	1.2 (1)		1.7 (11)	1.2 (72)	V	33
	1975		1.4 (7)		1.6 (1)		1.7 (2)	1.4 (15)	1.1 (42)	V	37
San Francisco	1969		1.4 (80)	1.6 (5)	1.2 (5)	1.5 (4)	1.0 (2)	1.3 (21)	0.9 (80)	V	245
	1970		0.9 (74)	1.7 (5)	0.9 (1)	1.1 (3)	0.9 (1)	1.1 (14)	0.9 (46)	V	245
	1971		0.7 (70)	1.8 (3)	1.2 (1)	1.5 (3)	1.4 (3)	1.1 (11)	0.8 (132)	V	24
	1972		0.7 (83)	0.8 (1)	0.5 (1)	0.8 (2)	0.9 (1)	1.0 (9)	0.8 (119)	V	26
	1973		0.7 (50)	0.8 (1)	1.3 (1)			0.8 (1)	0.8 (69)	V	31
	1974		0.6 (40)	1.1 (1)	0.8 (1)		0.7 (1)	0.7 (8)	0.7 (55)	V	33
	1975		0.5 (36)	0.6 (2)	1.2 (1)		0.7 (6)	0.8 (50)		V	37
Venezuela	1969								0.8 (22)	V	245
	1970								0.8 (23)	V	245
		Southern hemisphere									
Argentina	1969	1.3 (19)	1.4 (29)	1.2 (9)	1.3 (6)	1.3 (9)		1.3 (75)		V	245
	1970	1.4 (9)	1.4 (21)	1.3 (12)	1.5 (10)	1.4 (11)		1.3 (69)		V	245
	1971	1.4 (10)	1.3 (20)	1.3 (15)	1.6 (17)	1.3 (12)		1.2 (75)		V	21
	1972	1.4 (8)	1.3 (21)	1.3 (12)	1.5 (15)	1.3 (13)		1.2 (71)		V	21
	1973	0.97								V	21
	1974	0.95								V	21
	1975	0.9 (8)	1.0 (12)	0.9 (7)	1.0 (4)	1.0 (6)	1.0 (7)	1.0 (12)	1.0 (18)	V	71
	1976	1.0	0.8	1.0	1.0	0.9	1.0	0.9	1.0	V	71
Australia	1968	0.8 (79)	1.5 (98)	2.0 (26)	2.0 (14)	1.9 (8)	2.2 (14)	1.4 (75)	0.9 (75)	V	245
	1969	0.9 (108)	1.4 (98)	1.6 (27)	1.5 (11)	1.6 (7)	1.4 (13)	1.2 (136)	0.9 (112)	V	245
	1970	0.7 (448)	1.4 (182)	1.6 (42)	1.5 (34)	1.2 (20)	1.2 (13)	1.1 (180)	0.9 (246)	V	10

Country	Year	Age (y)								Adult bone type[a]	Reference
		Newborn or stillborn	< 1	1	2	3	4	5-19	> 19		
Australia (continued)	1971	0.8 (413)	1.6 (192)	1.8 (32)	1.6 (27)	1.3 (21)	1.2 (11)	1.1 (162)	0.8 (231)	V	11
	1972	0.8 (398)	1.6 (143)	1.7 (45)	1.8 (19)	1.9 (18)	1.8 (13)	1.2 (128)	1.0 (143)	V	
	1973	0.7 (264)	1.1 (172)	1.5 (27)	1.7 (18)	1.4 (21)	1.3 (16)	1.0 (129)	0.8 (150)	V	13
	1974	0.6 (348)	1.0 (178)	1.3 (25)	1.5 (16)	1.0 (19)	1.2 (4)	1.0 (83)	1.0 (107)	V	
	1975	0.6 (98)	1.0 (55)	1.3 (16)	1.2 (9)	2.2 (5)	1.4 (2)	1.0 (25)	1.0 (21)	V	
Brazil	1969			1.6 (1)	1.2 (1)			1.9 (5)	1.3 (39)	V	245
Chile	1969								1.7 (20)	V	
Indonesia	1970							1.5 (2)	0.7 (4)	V	119
	1971							0.3 (1)	0.4 (3)	V	
	1973							0.4 (1)	0.4 (6)	V	122
South Africa	1966 to 1969		1.1	———	———	1.3	———	2.0	0.5	R	245

[a] V = vertebra, R = rib, S = sternum, C = composite, N = normalized to whole skeleton.
[b] The data up to age of 4 years refer to Moscow only.
[c] Mainly V.

TABLE 12. STRONTIUM-90/Ca QUOTIENT IN ADULT VERTEBRAE BY COUNTRY

Northern hemisphere, 1962-1975

(pCi (gCa)$^{-1}$)

Year	Canada	Czechoslovakia	Denmark	France	Poland	USSR (Moscow)	United Kingdom	United States (New York)	Mean
1962	1.2		0.8		1.4			1.0	1.10
1963	1.7		1.2		1.6	1.7		1.6	1.56
1964	3.1	1.8	2.4		2.5	2.4		2.0	2.37
1965	3.1	2.2	2.7	2.2	2.5	3.1	1.9	2.1	2.47
1966	2.6	1.8	2.6	2.1	2.9	2.7	2.2	2.1	2.37
1967	2.5	1.9	2.1	2.2		2.3	1.6	1.9	2.07
1968	2.7	1.7	1.9	2.3		1.7	1.6	1.9	1.97
1969	2.2	1.8	1.3	2.0		1.7	1.5	1.7	1.74
1970		1.8	1.9			1.4	1.3	1.6	1.53
1971		1.5	1.7	1.8		1.2		1.4	1.52
1972			1.6	1.6				1.4	1.55
1973			1.5	1.5				1.3	1.43
1974			1.4					1.2	1.30
1975								1.1	

6. Transfer from diet to bone

71. The transfer factor linking diet and human bone P_{34} is defined by

$$P_{34} = \frac{\int_{-\infty}^{\infty} Q(t)\,dt}{\int_{-\infty}^{\infty} C(t)\,dt} \qquad (8)$$

where $Q(t)$ is the ^{90}Sr/Ca quotient in bone at time t, averaged over the population, and $C(t)$ is the corresponding quotient in the diet at time t, also averaged over the population.

72. In the 1969 report of the Committee (244) it was shown that if the values of $Q(t)$ and $C(t)$ are evaluated for discrete intervals of time of duration h, they are interrelated by the equation

$$Q(i) = \sum_{m=0}^{\infty} hC(ih-mh)\,K(mh) \qquad (9)$$

where $K(mh)$ is the transfer function discussed in the following paragraph. It is usual for $Q(t)$ and $C(t)$ to be determined for each calendar year, so in practice h has the value of 1 y. Equation 8 can be reformulated as

$$P_{34} = \frac{\sum_{i=-\infty}^{\infty} h \sum_{m=0}^{\infty} hC(ih-mh)\,K(mh)}{\sum_{i=-\infty}^{\infty} hC(ih)} = \sum_{m=0}^{\infty} hK(mh) \qquad (10)$$

73. In the 1972 report (245) several types of transfer function were tried in regression analyses of bone and diet data. The best fits were obtained with a function consisting of a rate term plus an exponential function term, first proposed by Coulon and Madelmont (77), with h = 1 y:

$$K(m) = c\,\delta_m + g \exp(-\mu m) \qquad (11)$$

where the first term is the rate term, accounting for that strontium in bone which is in rapid exchange with the plasma, the second term is the exponential term postulated to represent the values in bone after m years following a single intake, and δ_m is a function such that $\delta_m = 1$ when $m = 0$, and $\delta_m = 0$ when $m \neq 0$.

74. The bone ^{90}Sr/Ca quotients were fitted to the corresponding diet quotients for data taken from Australia, Denmark, New York, San Francisco and also to the average northern hemisphere data, using equation 9 and the transfer function of equation 11 (22). The ^{90}Sr/Ca quotient in the diet for the northern hemisphere was estimated by multiplying the corresponding values for milk (table 7) by 1.4.

75. The values of the parameters obtained by regression analysis are given in table 13, together with estimates of P_{34} obtained by the use of equation 10. Only the parameters for the Danish data have changed substantially since the 1972 report, and they are now more in line with those for other countries. Some comparisons of measured and predicted ^{90}Sr/Ca quotients in bone are shown in figure IX. The estimates of the transfer factor P_{34} vary little from one locality to another. The range of values shown in table 13 is 0.10-0.16, the average being 0.14.

TABLE 13. PARAMETERS OF THE TRANSFER FUNCTION OF ^{90}Sr BETWEEN DIET AND BONE

Obtained by regression analysis from data for various countries and areas

Parameter	*Australia*	*Denmark*	*United Kingdom*	*New York City*	*San Francisco*	*Northern hemisphere*
c (y^{-1})	0.001	0.037	–	0.017	0.021	0.023
g (y^{-1})	0.026	0.018	0.035	0.021	0.024	0.031
μ (y^{-1})	0.22	0.20	0.28	0.28	0.20	0.25
P_{34}	0.13	0.14	0.15	0.10	0.15	0.16

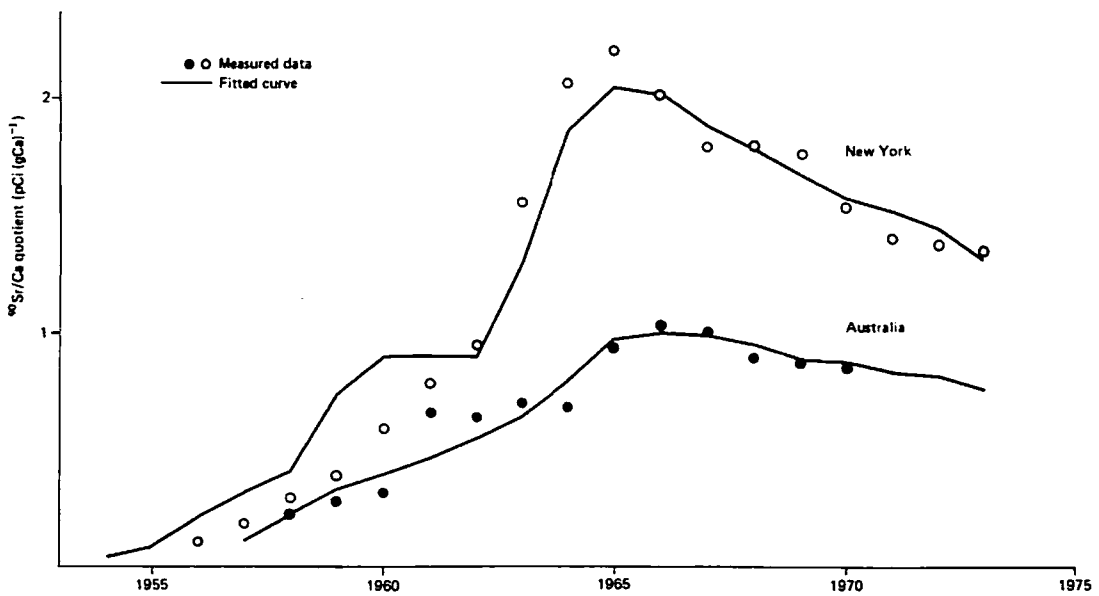


Figure IX. Variation of ^{90}Sr in bone in Australia and New York, 1955-1975

76. To account for the bone ^{90}Sr/Ca quotients in persons of all age groups, Bennett (36) has used an age-dependent transfer function. The ^{90}Sr/Ca quotient in bone at age i and year n, $Q(n, i)$, is postulated to be

$$Q(n,i) = (c_i + g_i)\,C(n,i) + \\ + [Q(n-1, i-1) - c_{i-1}\,C(n-1, i-1)]\,e^{-\lambda i} \qquad (12)$$

where $C(n, i)$ is the ^{90}Sr/Ca quotient in the diet of persons of age i in year n, and c_i and g_i are age-dependent model parameters. Bennet (36) has fitted equation 12 to the New York and San Francisco bone data for all age groups. For children under nine years of age the parameter c_i was found to be zero, consistent with a single exponential transfer model as originally proposed by Rivera (215). The best fit was obtained with a turnover rate of ^{90}Sr varying from about 100 per cent per year down to about 40 per cent per year in the pre-teenage years and then falling with age to about 20 per cent per year for adults. Beninson (18) had reported a similar variation in turnover rate with age from studies in Argentina. The fractional retention of strontium, i.e., the fraction of dietary intake incorporated into the skeleton, was also found by Bennett (37) to vary with age, being five to seven times higher for infants than for adults.

77. As shown in Annex A, the transfer factor of a sequence of steps in series in the compartment model is the product of the transfer factors of each step. The transfer factor of ^{90}Sr between fallout and bone P_{234} can therefore be calculated as $P_{234} = P_{23}\,P_{34}$. Using the

average values estimated for both factors, the P_{234} is calculated to be 0.7 pCi y $(gCa)^{-1}$ per mCi km^{-2}. This value is about 30 per cent higher than the one used in the 1972 report of the Committee, but due to the uncertainties involved in the calculations, this difference is not regarded as significant.

7. Transfer factor relating bone activity level and dose

78. In the compartment model described in paragraph 2, the transfer factor linking tissue radioactivity to tissue dose is P_{45}. The value of this factor for ^{90}Sr can be deduced from the following dosimetric considerations: The dose rate per unit beta activity in a small tissue-filled cavity in bone, $\dot{D}_0$, has been formulated by Spiers (225) as:

$$\dot{D}_0 = N_m \bar{E} (S_T/S_B)_m (K_B/K_T)$$

where $N_m = 1.17\ 10^6\ M^{-1}\ y^{-1}$ per pCi $(gCa)^{-1}$ is the number of beta particles emitted per year and unit mass of bone for each unit of the $^{90}Sr/Ca$ quotient, M being the mass of bone per unit mass of calcium ($M \simeq 5$) (160, 252); $\bar{E}$ is the effective energy of the beta rays emitted (for $^{90}Sr + ^{90}Y$, $\bar{E} = 1.13$ MeV); $(S_T/S_B)_m$ is the ratio of mass stopping powers in tissue and in bone = 1.07 (41), and K_B and K_T are the ratios of the effective range to total track length of beta particles in bone and soft tissue, respectively. They are assumed in this case to be unity (83). The dose-rate factor is therefore $\dot{D}_0 = 4.5$ mrad y^{-1} per pCi $(gCa)^{-1}$.

79. In order to obtain corresponding values for $\dot{D}_m$ and $\dot{D}_s$, the dose rate factors for bone marrow and for bone lining cells, which are the desired P_{45} transfer factors, use can be made of the $\dot{D}_m/\dot{D}_0$ and $\dot{D}_s/\dot{D}_0$ ratios estimated for cortical and trabecular bone by Spiers (226). These values are:

	$\dot{D}_m/\dot{D}_0$	$\dot{D}_s/\dot{D}_0$
Cortical contribution	0.055	0.082
Trabecular contribution	0.260	0.352
Total	0.32	0.43

The transfer factors P_{45} are therefore estimated to be:

P_{45} (marrow) = $(\dot{D}_m/\dot{D}_0)\dot{D}_0$ = 1.4 mrad per pCi y $(gCa)^{-1}$

P_{45} (bone lining cells) = $(\dot{D}_s/\dot{D}_0)\dot{D}_0$ = 1.9 mrad per pCi y $(gCa)^{-1}$.

8. Dose commitment from strontium-90

80. The dose commitment from ^{90}Sr released by nuclear explosions can be assessed using the environmental compartment model described in paragraph 2. The dominant exposure pathway is dietary intake, inhalation being completely negligible in comparison. The dose commitment D^c is related to the integrated deposition density F of ^{90}Sr by the following expression:

$$D^c = P_{234} P_{45} F$$

where P_{234} is the transfer factor linking integrated deposition density and the time-integral of the $^{90}Sr/Ca$ quotient in bone (para. 77) and P_{45} is the transfer factor linking the $^{90}Sr/Ca$ quotient in bone to the dose rate in the bone marrow or in the bone lining cells (para. 79).

81. The integrated deposition density in each hemisphere from all nuclear explosions to the end of 1975 can be calculated by applying the population weighting procedure described in paragraph 47 to the data presented in table 3. The results are (mCi km^{-2}):

	Northern hemisphere	*Southern hemisphere*
Entire hemisphere	56.5	17.6
Temperate zone	85.1	24.5

82. Table 14 presents the dose commitment from ^{90}Sr to the populations of each hemisphere and to the populations of the temperate latitudes of each hemisphere.

TABLE 14. DOSE COMMITMENTS TO BONE TISSUES FROM ^{90}Sr PRODUCED IN ALL NUCLEAR EXPLOSIONS UP TO THE END OF 1975

(mrad)

	Northern hemisphere		*Southern hemisphere*	
Tissue	*Temperate zone*	*Population-weighted average*	*Temperate zone*	*Population-weighted average*
Bone marrow	85	56	24	17
Endosteal cells	116	77	33	24

83. The dose commitments to the world population, calculated from the global mean integrated deposition density given in paragraph 47, are 52 mrad for bone marrow and 71 mrad for bone lining cells. As the total activity of ^{90}Sr released to the environment by nuclear tests is approximately 16 MCi (table 2), the collective dose commitments per unit activity of ^{90}Sr released, assessed by the procedures outlined in Annex A, are approximately 13 man rad Ci^{-1} for bone marrow and 18 man rad Ci^{-1} for bone lining cells, for the geographic pattern of past nuclear tests.

G. STRONTIUM-89

84. Strontium-89 has a half-life of 50.5 d and decays with the emission of a beta particle with maximum

energy of 1.46 MeV. It is one of the main components of fallout activity in the first few months after a nuclear test. It has been extensively measured in fallout since 1961 (111); the latitudinal distribution of the integrated deposition density is shown in table 15.

TABLE 15. LATITUDINAL DISTRIBUTION OF ^{89}Sr INTEGRATED DEPOSITION DENSITY, 1961-1963

Latitude band	*Area of band (10^6 km^2)*	*Relative population of band (%)*	*Integrated deposition density of ^{89}Sr (mCi km^{-2})*
70°-80°N	11.6	~0	34
60°-70°N	18.9	0.4	210
50°-60°N	25.6	12.2	250
40°-50°N	31.5	13.8	326
30°-40°N	36.4	18.2	288
20°-30°N	40.2	29.2	218
10°-20°N	42.8	9.8	121
0°-10°N	44.1	5.6	104
0°-10°S	44.1	5.8	88
10°-20°S	42.8	1.8	9
20°-30°S	40.2	1.6	19
30°-40°S	36.4	1.4	11
40°-50°S	31.5	0.1	11
50°-60°S	25.6	0.05	

Source: Reference 111.

85. Strontium-89 was measured in milk at some 63 cities in the United States between 1962 and 1966 (204). The time-integral of the concentration for this period was 95.5 pCi y l^{-1}. O'Brien (195) has estimated the transfer factor P_{34} linking the time-integrals of the $^{89}Sr/Ca$ quotient in milk and in human bone. Using the infinite time-integrals of the retention functions for cancellous bone for ^{89}Sr and ^{90}Sr presented in the ICRP alkaline earth metabolic model (160), it was estimated that the transfer factor P_{34}^{milk} for ^{89}Sr is 0.022 of the total diet P_{23} for ^{90}Sr. O'Brien (195) estimated the factor P_{45} for ^{89}Sr to be 0.71 mrad per pCi y (gCa)$^{-1}$, which, using a value of 0.14 for the P_{34} of ^{90}Sr, leads to a combined factor P_{345}^{milk} of 0.0022 mrad per pCi y (gCa)$^{-1}$. With the above time-integral of the $^{89}Sr/Ca$ quotient in milk, the *per caput* bone-marrow dose in the United States between 1961 and 1966 is estimated to be 0.21 mrad.

86. Relating this value to the relevant integrated deposition density of ^{89}Sr, it is estimated that the bone marrow dose commitment to the population in the temperate zone of the northern hemisphere from all tests up to 1970 is approximately 0.4 mrad.

87. As the ratio of activities $^{89}Sr/^{90}Sr$ at the time of fission is approximately 185 (62), the total atmospheric input of ^{89}Sr is estimated to have been about 2.8 10^9 Ci. The collective dose commitment to the bone marrow per unit activity release of ^{89}Sr, calculated by the procedures outlined in Annex A is approximately 4 10^{-4} man rad Ci^{-1} for the past pattern of nuclear explosions.

H. RUTHENIUM-106

88. Ruthenium-106 has a half-life of 365 days and decays to ^{106}Rh by pure beta decay with a maximum energy of 0.039 MeV. The 30-s half-life ^{106}Rh decays with a maximum beta energy of 3.45 MeV and also emits several gamma rays.

89. The time-integral of the concentration of ^{106}Ru in air can be estimated from that for ^{144}Ce given in table 20. Cerium-144 has a half-life of 285 d, so that the $^{106}Ru/^{144}Ce$ activity ratio will only change with a half-time of about 3.5 y. The ratio of the integrated deposition densities of ^{106}Ru and ^{144}Ce was 0.51 for Chilton, United Kingdom, 1967-1970 (61) and 0.53 for Pittsburgh, United States, 1961-1963 (110), and at Bombay, India, 1966-1969 (102), the ratio of the time-integrals of the activity concentrations in air was 0.38. Assuming a value of 0.50 for the ratio of the time-integrals of the activity concentrations in air of ^{106}Ru and ^{144}Ce, and using the estimates for the latter, time-integral for ^{106}Ru is estimated to be 1.5 pCi y m^{-3} in the northern hemisphere and 0.35 pCi y m^{-3} in the southern.

90. Assuming that the activity is present as an aerosol of about 0.5-μm particle size and using the ICRP lung model (135, 136) with class Y parameters, the transfer factor between activity in air and lung dose P_{145} is estimated to be 27.2 mrad per pCi y m^{-3} for the dose to the pulmonary region of the lung. The resulting dose commitments to the pulmonary region from all tests to the end of 1975 are respectively 41 and 10 mrad in the northern and southern hemispheres.

91. The total injection of ^{106}Ru, assessed from that of ^{90}Sr using the corresponding activity ratio at the time of fission, has been about 3.3 10^8 Ci. Using the procedures described in Annex A, the collective dose commitment to the lung per unit activity of ^{106}Ru released is estimated to be about 0.4 man rad Ci^{-1} for the past pattern of nuclear explosions.

I. IODINE-131

92. Iodine-131 is a beta emitter with a half-life of 8 d, and a maximum beta energy of 0.81 MeV, with the emission of gamma rays of 0.72 and 0.36 MeV and other energies. Due to its short half-life, ^{131}I is present in the long-range tropospheric fallout only shortly after atmospheric detonations. It is unlikely that the clouds of radioactive debris become well mixed during periods comparable to the mean residence time of an aerosol in the troposphere. The concentration of ^{131}I in surface air at a particular location, therefore, will depend strongly on meteorological conditions and will not necessarily be representative of a latitude band or even of a large region.

93. Fresh milk dominates as a source of ^{131}I intake in areas where it is a major diet component, because of the large areas scavenged by the grazing animal and also because of the short storage period of milk. The transfer of ^{131}I from deposition on grass to milk has been estimated from laboratory experiments (97) and from fallout field measurements (17), and varies widely, depending mainly on the density of the herbage and on cattle-feeding practices. Table 16 gives the reported time-integrated concentrations in milk over the period 1966-1974 in a number of countries, mainly in the southern hemisphere, and some 1976 data from France and Japan. The values reported for the southern hemisphere in 1974 were higher than those in 1972 and 1973 and approached the levels observed in the years 1967-1971.

TABLE 16. CONCENTRATION OF ^{131}I IN MILK AND THYROID DOSE TO INFANTS AT VARIOUS LOCATIONS, 1966-1974[a]

Location	Integrated milk concentration (nCi d l^{-1})									Calculated thyroid dose to infants (mrad)								
	1966	1967	1968	1969	1970	1971	1972	1973	1974	1966	1967	1968	1969	1970	1971	1972	1973	1974
Northern hemisphere																		
Japan[b, c]																		
Chiba	0.42	2.75					0.37	0.9		5	32					4	10	
Miyagi								1.2									14	
United Kingdom[b, c]		0.60									7							
United States																		
Sebastian City[c]	9.3									107								
Houston[c]		3.7									43							
Nashville[b, c]							0.90									10		
Southern hemisphere																		
Argentina																		
Bariloche	7.6	1.4							4.9	88	16							56
Buenos Aires	27	4.3	2.5		4.6	4.17	7.0	1.7	8.5	310	50	28		52	48	81	20	97
Salta	15	1.8							6.9	174	21							79
Australia[c]																		
Malanda (highest)[d]	11	10.4	4.5		5.8	5.4	0.17	0.05	2.47	127	120	52		67	62	2	0.6	28
Hobart-Launceston[e]	1.5	0.38	0.79		0.86	0.35	0.04	0.04	0.34	17	4	9		10	4	0.4	0.4	3.9
Country average							0.02	0.07	0.78	43	10	16		15	13	1.3	0.8	9.0
Bolivia																		
La Paz					11	2.4		5	3.0					120	30	44	60	35
Brazil																		
Guanabara					3.6									42				
Chile																		
Santiago	4.0				3.0	5.2	1.9	0.3	2.1	50	9	10		30	60	22	3	24
Colombia																		
Bogota	0.4	0.4	0.4		0.9	0.7		1.5	0.1	5	5	10		10	8		18	1
Ecuador																		
Quito	2.5		0.3						1.3	30		10						15
Fiji																		
Suva[c]	18[f]	2.9	4.4		3.7	2.9	0.4	0.4	2.4	210	33	51		43	33	5	5	28
Madagascar																		
Diego-Suarez	13	1.8	6.5			6.4				160	22	80			75			
New Caledonia																		
Noumea		0.4			3.5	2.6			16		5			40	30			184
New Zealand[c]	1.5	0.4	0.7		0.7	0.4	0.4	0.4	0.4	17	5	8		8	5	5	5	5

TABLE 16 *(continued)*

Location	Integrated milk concentration (nCi d l^{-1})									Calculated thyroid dose to infants (mrad)								
	1966	*1967*	*1968*	*1969*	*1970*	*1971*	*1972*	*1973*	*1974*	*1966*	*1967*	*1968*	*1969*	*1970*	*1971*	*1972*	*1973*	*1974*
Southern hemisphere (continued)																		
Peru																		
Arequipa			6		7.5	2.9			16			70		90	35			
Lima	6		4						2.1	70	23	50		10	13			
Tacna			10						1.2			120						
Samoa																		
Apia	15[f]	8.4	3.3		6.2	7.3	0.4	1.1	4.4	170	97	38		71	84	5	13	51
Society Islands																		
Tahiti		4.7	4.9		11	18	1.0	11	59		55	60		130	210	12	130	680
South Africa																		
Cape Town					1.5									17				
Pretoria					8.0	11.1								92	127			

[a] There are 1976 data: France (0.91, 10); Japan: Fukushuma (0.95, 11), Chiba (0.36, 4), Fukoku (0.33, 4). The first figure in the parentheses is the integrated milk concentration and the second is the thyroid dose, in the same units as in the table.

[b] The integrated concentration has been taken to be numerically equal to 10 times the highest observed concentration in nCi l^{-1}.

[c] The dose is assumed to be the time-integrated concentration multiplied by 11.5 mrad pCi^{-1} d^{-1} l.

[d] In 1973, the highest integrated milk concentration was measured at Perth (0.27 nCi d l^{-1}).

[e] Lowest.

[f] Value based on an extrapolation.

94. As ^{131}I concentrates in bovine thyroid, this organ is a suitable biological indicator of the presence of ^{131}I in the local environment. Beninson (19) measured the concentration of ^{131}I in bovine milk and thyroid in Argentina during the period 1966-1970. The ratio between the time-integral of the ^{131}I concentration in thyroid and that in milk was fairly constant for the different years and had a value of about 500. Monitoring of ^{131}I in bovine thyroid carried out in Czechoslovakia (66) confirms the very high sensitivity of this method of surveillance for ^{131}I in the environment.

95. Infants receive higher doses in their thyroids than do adults for a given intake of ^{131}I, the main reason being the smaller thyroid mass. A mass of 2 g was used for estimating doses to infant thyroids. Estimates of the dose in infant thyroids per unit activity of ^{131}I reaching the organ range from 15.5 to 18.5 mrad nCi^{-1} (179, 189), and a value of 16.5 was used in the 1972 report of the Committee. Assuming that infants consume 0.7 l of fresh milk per day and that all the ^{131}I ingested is taken up by the thyroid, the P_{345} transfer factor (relating thyroid dose in infants to the time-integrated iodine-131 concentration in milk) can be estimated to be about 11.5 mrad per nCi d l^{-1}.

96. Table 16 presents estimates of the dose in infant thyroids, as calculated with the assumptions mentioned above. They should be regarded as the highest individual doses in the areas for which the assumed consumption is realistic, and as clear overestimates in areas such as the Society Islands where fresh cow's milk is only a small fraction of the total milk consumed by infants. The dose to adults should be at least an order of magnitude lower, because the mass of their thyroids is about ten times larger, and their milk consumption is smaller.

J. CAESIUM-137

97. Caesium-137 is a beta emitter with a maximum beta energy of 1.17 MeV, which decays with the emission of gamma rays of 0.66 MeV. It has a half-life of 30 y, very close to that of ^{90}Sr, and since the measured activity ratio of $^{137}Cs/^{90}Sr$ in deposition at many sites and over a long time has been fairly constant at about 1.6 (245), it is useful to use the more complete data on ^{90}Sr to estimate the deposition of ^{137}Cs. In this way also the latitudinal distribution of ^{137}Cs integrated deposition density can be estimated from the ^{90}Sr data of table 3.

1. Caesium-137 in the environment

98. Since the half-life of ^{137}Cs is relatively long, the assessment of dose commitments requires the understanding of the behaviour of this radionuclide in the environment. A recent review of the literature on this subject has been published by Moiseev *et al.* (262). The deposition of ^{137}Cs occurs over land and over the oceans. As in the case of ^{90}Sr, it has been found that fallout over land is the more important pathway as far as dose commitments to man are concerned.

99. After deposition over land, caesium-137 enters the dietary pathway, being taken up by plants either through the root system or by direct uptake by the leaves. Caesium-137 seems to become more strongly fixed in the soil than ^{90}Sr does (14, 114, 159, 267), but its availability to plants depends markedly on the soil type and has been found to decrease in time (256). In a sandy soil in Massachussetts (United States), Hardy (114) found that 84 per cent of the fallout ^{137}Cs was in the top 4 cm of soil, and 97 per cent was in the top 31 cm. Marei *et al.* (159) have identified regions in the USSR where the soil is wet, peaty and podzolic, from which the transfer of ^{137}Cs into the food chain is 10 times higher than for other regions. Other regions of the world where there are soils giving rise to high ^{137}Cs transfer into diet have also been identified, for example, in the Faroe Islands (3), New Zealand (188) and Sweden (151). The mechanism of such enhanced transfer has also been studied (94). Much smaller amounts of ^{137}Cs than of ^{90}Sr are leached out of the soil to enter rivers and lakes.

100. Regarding deposition of ^{137}Cs on the oceans, measurements made on sediments of the Atlantic Ocean indicate that only about 3 per cent of the fallout ^{137}Cs has reached the bottom (193). Activity concentrations in surface waters of the open ocean are about 0.2 pCi l^{-1} (46), and in the deep ocean they are lower by a factor of about 30. Hodge *et al.* (127), from measurements of ^{137}Cs concentrations in Pacific tuna, estimated the half residence-time of ^{137}Cs in surface waters to be about 17 y.

101. Marine food chains seem to be of secondary importance in relation to human intakes. The reported concentration factors between sea water and mose biota are about 50 (93, 191, 214, 240). It has been estimated that in Japan, between 1966 and 1971, only about 8 per cent of the dietary intake of ^{137}Cs came from the consumption of fish products (240).

2. Levels in diet

102. Since ^{137}Cs is an alkali metal like potassium, and since the concentration of potassium in lean body mass is constant (225), it is convenient to express the ^{137}Cs activity in food and in the human body as the $^{137}Cs/K$ quotient, usually in picocuries per gram. Data on the ^{137}Cs concentration in milk and on its daily intake from the total diet are shown in tables 4 and 6. Data available for 1973 and 1974 indicate that, generally speaking, levels are still falling. The transfer of ^{137}Cs from deposition to diet is normally high during the first year after deposition and relatively small subsequently. Concentrations in milk are strongly dependent on deposition in the same year. That explains why in the northern hemisphere the milk concentrations on the average decreased from 1966 to 1969, were relatively stable from 1969 to 1971, and decreased again from 1971 to 1973.

103. The transfer of ^{137}Cs from deposition to diet can be studied quantitatively using an approach similar to that for ^{90}Sr (paras. 55-69). The measured $^{137}Cs/K$ quotients in the various components of the Danish diet are plotted against time in figure X (2). Evans and

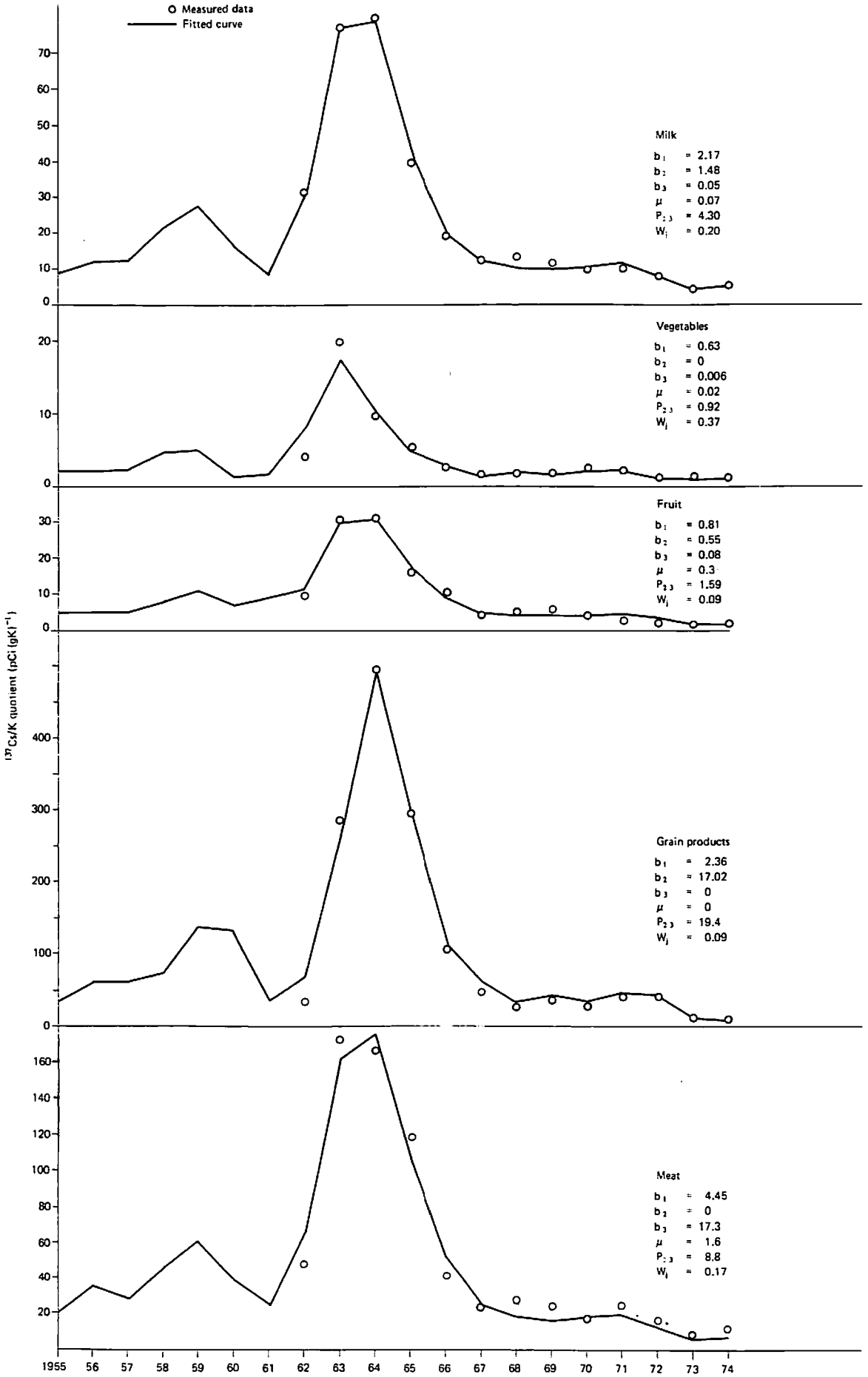


Figure X. Variation of ^{137}Cs in various diet components in Denmark, 1955-1974. The unit for parameters b_1, b_2, b_3 is pCi $(gK)^{-1}$ per mCi km^{-2}. The unit for parameter μ is y^{-1}. The unit for the transfer factor P_{23} is pCi y $(gK)^{-1}$ per mCi km^{-2}.

TABLE 17. PARAMETERS OF THE TRANSFER FUNCTION BETWEEN ^{137}Cs FALLOUT AND DIET

Obtained by regression analysis from Danish data

Parameter[a]	Milk products	Grain products	Meat, fish, eggs	Vege-tables	Fruit	Total composite diet
b_1	2.17	2.36	4.45	0.63	0.81	1.56
b_2	1.48	17.02	0.0	0.0	0.55	2.21
b_3	0.05	0.02	17.24	0.006	0.08	0.04
μ	0.07	0.0	1.60	0.02	0.30	0.12
P_{23}^j	4.32	19.38	8.80	0.92	1.59	4.08
W_j	0.20	0.09	0.17	0.37	0.09	1.00
$W_j P_{23}^j$	0.86	1.74	1.50	0.34	0.14	4.08
Total diet P_{23}			4.58			4.08

[a]The unit for parameters b_1, b_2, b_3 is pCi (gK)$^{-1}$ per mCi km^{-2}. The unit for parameter μ is y^{-1}. The unit for the transfer factor $P_2 I_3$ is pCi y (gK)$^{-1}$ per mCi km^{-2}. W_j is the fractional contribution of component j to the total K diet.

Bennett (86) have carried out a regression analysis using these data and the annual deposition data, with a transfer function of the same form as that shown in paragraph 58 for ^{90}Sr. The figure also shows the curves fitted to the data with the parameters given in table 17. In Denmark the main contribution to the intake of ^{137}Cs has been from meat and grain products, with a sizeable contribution from milk. Fruit and vegetables contribute much smaller amounts. The same is true of Chicago (United States). In Japan, however, the main contribution has been from cereals (240). For all foods the transfer seems to be rapid, being essentially completed within the first two years after deposition.

104. The same transfer function was also fitted to the ^{137}Cs/K quotients in fresh milk in several countries, and the resulting parameters are shown in table 18. The transfer factors P_{23}^{milk} linking deposition density and the time-integrated ^{137}Cs/K quotient in milk for Argentina, Australia, Faroe Islands, New Zealand, Norway and USSR are significantly greater than those for Denmark and the United States. The value reported for Finland, 15.8 pCi y (gK)$^{-1}$ per mCi km^{-2} (65), is also in this higher range. It should be noted that parameters relating to Denmark in table 18 are for fresh milk, while those in the first column table 17 refer to milk products.

105. The results of the regression analysis for the estimation of P_{23}, or its components such as P_{23}^{milk}, are consistent with the assessments carried out by the Committee for its 1969 and 1972 reports (244, 245). A value of 4.1 pCi y (gK)$^{-1}$ per mCi km^{-2} was estimated in these reports for the factor P_{23}, identical with that shown in table 17, which was derived by regression analysis. The same value, rounded to 4 pCi (gK)$^{-1}$ per mCi km^{-2}, will be used in this report for the purpose of assessing dose commitments from ^{137}Cs for the world population. This value of the transfer factor adequately represents some areas in the northern hemisphere, but on the available evidence discussed above, it would appear to underestimate P_{23} for other areas, especially in the southern hemisphere.

106. The latitudinal distribution of ^{137}Cs deposition density in 1972 (assessed from the ^{90}Sr data assuming a constant ^{137}Cs/^{90}Sr activity ratio) is shown as the curve in figure XI. Also shown in figure XI are the ^{137}Cs concentrations in milk in 1972 at various localities. The ^{137}Cs milk concentrations for a number of them depart markedly from a general correlation with the deposition data. Since data on ^{137}Cs concentration in foods are not available for many areas of the world, particularly in the tropical regions, it is not possible to assess what the importance of this effect might be on the global scale.

TABLE 18. PARAMETERS OF THE TRANSFER FUNCTION FROM ^{137}Cs FALLOUT TO MILK

Obtained by regression analysis of data for various countries and areas

Parameter[a]	Argentina	Australia	Denmark	Faroe Islands	New Zealand	Norway	USSR	United Kingdom	United States
b_1	2.21	7.24	2.37	6.80	6.79	3.52	4.43	1.75	2.28
b_2	0.00	4.78	0.69	5.44	0.68	2.26	0.22	1.61	1.34
b_3	1.80	0.30	0.06	2.83	3.62	2.63	0.31	0.03	0.00
μ	0.27	0.18	0.30	0.17	0.51	0.24	0.18	0.023	0.05
P_{23}^{milk}	8.02	13.59	3.23	27.51	12.91	15.48	6.22	4.75	3.63

[a]The unit for parameters b_1, b_2, b_3, is pCi (gK)$^{-1}$ per mCi km^{-2}. The unit for parameter μ is y^{-1}. The unit for the transfer factor P_{23}^{milk} is pCi y (gK)$^{-1}$ per mCi km^{-2}.

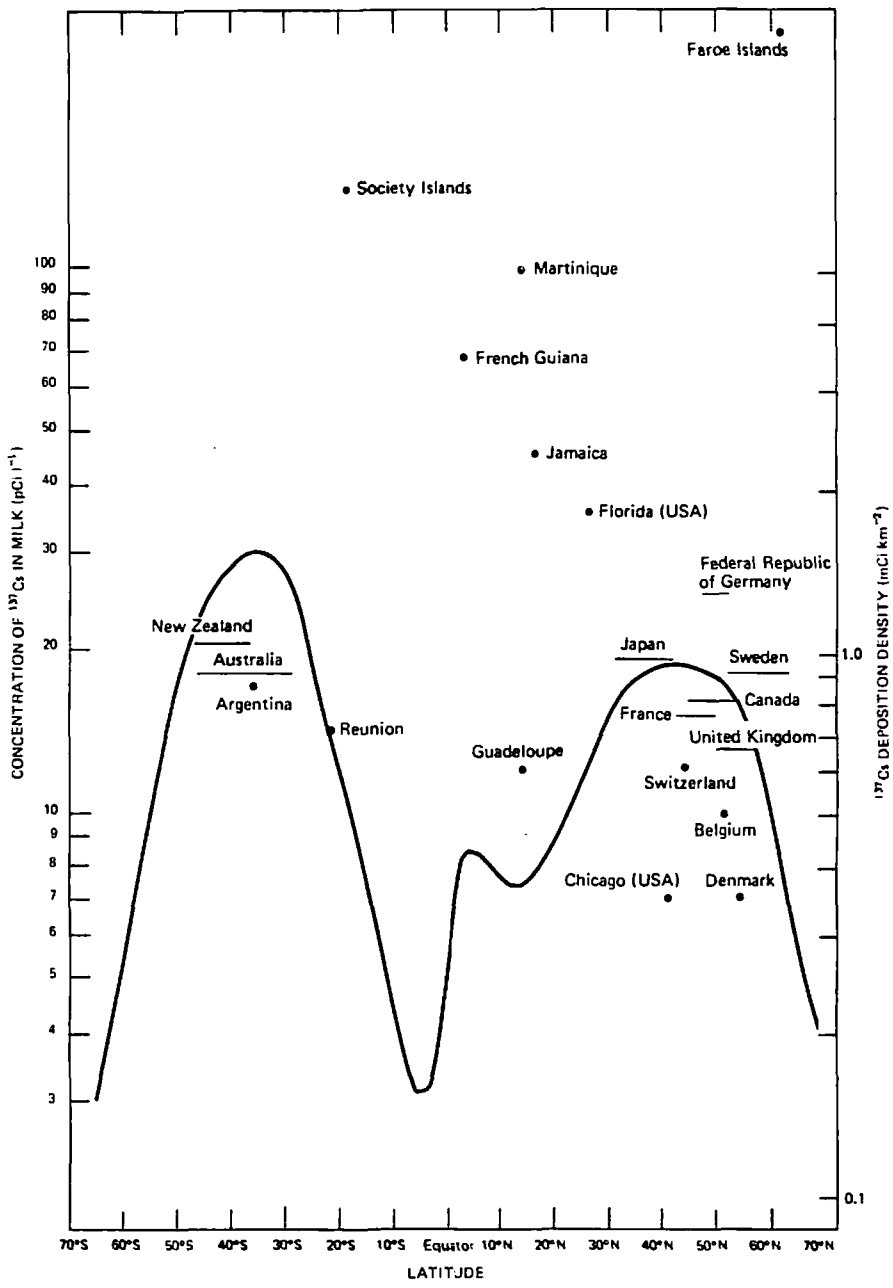


Figure XI. Latitudinal distribution of ^{137}Cs deposition density (curve) and the concentration of ^{137}Cs in milk at various locations (dots and segments), 1972

3. Caesium-137 in the human body

107. Caesium-137 ingested by man is distributed in the body, with about 80 per cent being deposited in muscle and 8 per cent in bone (225). About 10 per cent of the activity taken in is eliminated rapidly, with a biological half-life of about 1 d, while the remaining 90 per cent is excreted at a lower rate (225). The biological half-life of this main fraction varies between less than 50 d to more than 200 d in adults (43, 124, 245) and is shorter in children than in adults (124). Owing to this relatively short biological half-life, the activity of ^{137}Cs in the body tends to follow the fluctuations of the concentration of ^{137}Cs in the diet.

108. Table 19 summarizes the information on ^{137}Cs/K quotients in the human body in the period 1964-1974. For all localities, the values have continued to decrease since the 1972 report of the Committee. The ^{137}Cs/K quotients in subarctic populations are between two and three orders of magnitude higher than those in the middle latitudes, as shown by data from Finland, Norway and Sweden and from the northern USSR and United States (Alaska) (123, 200, 210, 238, 250). These high values are due to the lichen-reindeer (or caribou) food chain (245).

109. The short biological half-life of caesium in the body makes it possible to assess the transfer factor between diet and body P_{34} from the ^{137}Cs/k quotients integrated over a few years. Using this procedure, an average value of 3 is derived from the data of tables 6 and 19 converted into ^{137}Cs/K quotients, which is practically identical to the value used in the 1969 and 1972 reports, namely 2.9.

TABLE 19. CAESIUM-137/POTASSIUM QUOTIENT IN THE HUMAN BODY
(pCi (gK)$^{-1}$)

Location	*Approximate latitude (degrees N or S)*	*Sex*	*1964*	*1965*	*1966*	*1967*	*1968*	*1969*	*1970*	*1971*	*1972*	*1973*	*1974*	*1975*	*Reference*
						Northern hemisphere									
Belgium	50	M, F	158	135	87	50	29								244
Canada (Ottawa)	45	M, F		170											175
Denmark	55-60	M, F	185	168	106	65	46	40	23	13	16	11	10	11	2
Egypt	30	M, F				23	14		12						181
Finland	60	M, F		182	150	107	72	53	44	34	38	37	28	29	231, 232
France	50	M, F	227	194	93	64	36	32	26	28	28	21	18	17	198
Germany, Fed. Rep. of															
Karlsruhe	49	M, F	151	111	81	49	27	16	15	15	17	11	9	12	
Düsseldorf	51	M	243	186	128	76	41	32	31	22	30	23	19	15	52
Israel	35	M					48								
Japan	30-45	M	93	77	54	33	20	14	13	16	12	10	9	8	186, 239
Norway	60	M, F		430	290										132
Poland	50-55	M, F	164	185		71									152
Sweden (Stockholm)	60	M, F	205	187	139	107	74	54	47	46	38	31	22		233
Switzerland (Geneva)	45	M	206	179	103	54	30	24	21	23	19				
		F	139	121	66	41	26	19	18	22	19				129
USSR															
Moscow	55	M	258			50	34	29	38						266
		F				42	27	22	36						265
Leningrad	60	M, F	174	142	92	68	70								
United Kingdom															
London area	50	M		148	89	45									101
		F	149	109	60	33									
West Cumberland	55	M	257	190	110	52	30								
United States															
Country average	25-50	M, F	141	109	60	35	17								104
Florida	25-30	M, F		149	132	120									216
West Berlin	52	M, F				68	49	47	36	29	25	19	10	11	52
						Subarctic region									
Canada															
Eastern (Eskimos)	60-70	M			5 800										42
Central (Eskimos)	60-70	M				11 000									
Finland															123
Inari (reindeer herders)	70	M	7 800	9 000	7 800	5 500	5 200	3 400	3 100	4 100					
		F	8 800	11 200	7 900	3 800	4 200	3 600	2 800	3 300					
USSR															
Murmansk	65-70	M	14 000	18 000	25 500	17 500	16 500	15 500	12 500	11 500	9 000				238
United States															
Alaska	65-70	M	9 100	6 600	4 900	4 300	2 400								210
						Southern hemisphere									
Argentina	35-40				31	20	16	13	15	14	12	10	9	4	21, 71
Australia	30-40			65	42	37	18		16	30	25	17			11

110. An alternative approach for the derivation of P_{34} is the assessment by regression analysis of the parameters of a postulated transfer function relating diet to body. Applying this procedure to the data from Denmark and the United States, and assuming a single exponential transfer function, the estimated values of P_{34} are 2.6 for Denmark and 3.0 for the United States (86), in good agreement with the value of 3 mentioned in paragraph 109.

4. Dose commitment from caesium-137

111. The combined transfer factor P_{234}, linking deposition to the ^{137}Cs/K quotient in the body, is the product of P_{23} and P_{34}. From the estimated average values for these two factors (paras. 105 and 109), a value of 12 pCi y $(gK)^{-1}$ per mCi km^{-2} is calculated for the combined factor P_{234}.

112. An alternative procedure for the assessment of P_{234} is the direct use of the time-integrated ^{137}Cs/K quotient in the body $\int Q dt$ and the integrated deposition density F, both over the same period of several years, the factor being $P_{234} = \int Q dt / F$. This procedure, applied to data from Argentina in the period 1966-1974 (16, 21), estimates the factor P_{234} to be 11 pCi $(gK)^{-1}$ per mCi km^{-2}. For Stockholm the time-integrated ^{137}Cs/K quotient in the body in the period 1962-1972, is 1053 pCi y $(gK)^{-1}$ (244, 245), while for the same period the integrated deposition density of ^{137}Cs in the region (at Tumba, near Stockholm) is 58 mCi km^{-2}. This gives a value of P_{234} of 18 pCi y $(gK)^{-1}$ per mCi km^{-2}, about 50 per cent higher than the average estimate given above. Aarkrog estimated P_{234} in Denmark by regression analysis from the body ^{137}Cs/K quotients and the annual deposition densities, obtaining a value of about 11 pCi y $(gK)^{-1}$ per mCi km^{-2} (2).

113. The transfer factor P_{234} could vary mainly as a result of variations of P_{23} with the local conditions, particularly soil characteristics (para. 99) and the nature of the diet. In the 1972 report (245), the Committee assessed the possible range of P_{23} values, based on USSR data and the conservative assumption that available ^{137}Cs decreased only by radioactive decay. This range, multiplied by the value of P_{34} given in paragraph 109, implies that P_{234} would be smaller than 22 pCi y $(gK)^{-1}$ per mCi km^{-2}. The use of a value of 12 pCi $(gK)^{-1}$ per mCi km^{-2} for P_{234} (para. 112), for the purpose of assessing dose commitments, could therefore not underestimate these commitments by a factor of more than two.

114. As was shown in the 1969 report of the Committee (244), the transfer factor P_{45}, linking tissue activity and tissue dose, is approximately independent of age if expressed as dose per unit of the time-integrated ^{137}Cs/K quotient. The value of $P_{45} = 1.8\ 10^{-2}$ mrad per pCi y $(gK)^{-1}$, combined with the estimate of $P_{234} = 12$ pCi y $(gK)^{-1}$ per mCi km^{-2}, gives a value for the overall transfer factor P_{2345} of about 0.2 mrad per mCi km^{-2}.

115. The integrated deposition density of ^{137}Cs can be assessed from that of ^{90}Sr (paras. 47 and 81), using an activity ratio of 1.6 (para. 97). The values are (mCi km^{-2}): temperate latitudes of the northern hemisphere, 136; temperate latitudes of the southern hemisphere, 39; global value weighted by the population distribution, 84. The resulting dose commitments are respectively 27 and 8 mrad for the populations in the temperate latitudes of the northern and southern hemisphere and 17 mrad for the world population.

116. It is to be noted that the above dose commitments are based upon information obtained in areas where ^{137}Cs in the soil becomes unavailable to plants fairly rapidly. For populations consuming food from other types of soil, the dose commitments could be higher (para. 113), and for people in the subarctic regions eating reindeer and caribou meat, the dose commitments are indeed much larger. Assuming, however, that the contribution of such different situations to the total collective dose is not large, it can be estimated that the collective dose commitment from internal exposure, per unit activity of ^{137}Cs released, is of the order of 3 man rad Ci^{-1} for the past pattern of nuclear explosions.

K. CAESIUM-136

117. Caesium-136 is a beta emitter with a half-life of 13.5 d. The maximum beta energy is 0.66 MeV, and several gamma rays with energies up to 1.25 Mev are emitted. Since it must be produced directly by fission and not by beta decay, because ^{136}Xe is stable, the activity produced in nuclear tests is fairly small. By using the ^{136}Cs/^{140}Ba fission yield ratio and the deposition-to-milk transfer factors of ^{137}Cs and ^{140}Ba, O'Brien (195) has estimated the integrated deposition density of ^{136}Cs and the time-integrated concentration in milk in the United States between 1961 and 1965. These calculated values agree roughly with the few measurements which have been made of ^{136}Cs (177). The time-integrated concentration in milk in the United States between 1961 and 1965 was estimated to be 4.2 pCi y l^{-1}. Using data on trasfer factors for ^{137}Cs and ^{140}Ba as a guide, O'Brien estimated P_{345} (milk-to-dose) for ^{136}Cs to be $1.3\ 10^{-3}$ mrad per pCi y l^{-1}. The estimated dose commitment for the population of the temperate regions of the northern hemisphere from all tests to 1970 is 0.01 mrad.

L. BARIUM-140

118. Barium-140 is a beta emitter with a half-life of 12.8 d and a maximum beta energy of 1.02 MeV. It emits several gamma rays. Its daughter product, the 40.2-h half-life ^{140}La, decays with a 2.18-MeV maximum-energy beta emission and several gamma rays, with energies up to 1.6 MeV. Barium-140 is measurable in fallout only for a few weeks after a nuclear explosion. This radionuclide was measured in the pasteurized milk supply networks of the United States by the Public Health Service between 1961 and 1966 (204). The time-integrated concentration in milk was 16.2 pCi y l^{-1} for this period. O'Brien (195) estimated the factor P_{45} for ^{140}Ba to be about 3.0 mrad per pCi y $(gCa)^{-1}$ in bone. In addition, using the P_{34} value for ^{90}Sr together with the ICRP model for alkaline-earth metabolism (160), the factor P_{34}^{milk} for ^{140}Ba was estimated to be

$5.5\ 10^{-5}$. With these values, in the United States the mean dose to bone marrow for the period 1961-1965 is estimated to be $2.6\ 10^{-3}$ mrad. The dose commitment in the temperate zone of the northern hemisphere is estimated to be $6\ 10^{-3}$ mrad, assuming an average consumption of 0.6 l of milk per day.

M. CERIUM-144

119. Cerium-144 has been widely measured in air and in fallout (61, 249). It has a half-life of 285 d and together with its daughter decay product, the 1.7-min ^{144}Pr, emits beta particles of 2.99-MeV maximum energy and several gamma rays. Table 20 shows, for a number of sites in each hemisphere, the ratio of the integrated deposition density of ^{144}Ce to that of ^{90}Sr, together with similar ratios of the time-integrated activity concentrations in air (obtained by the sum of the average monthly activity concentrations over the specified period of time). These ratios are indicated in the table as $\Sigma^{144}Ce/\Sigma^{90}Sr$. Using a value of 15 as representative for the ratio for all tests up to 1974, the mean integrated deposition density of ^{144}Ce is estimated to be (mCi km^{-2}): northern temperate zone, 1257; southern temperate zone, 360; world (population-weighted), 765, based on data of table 2 and paragraph 47.

TABLE 20. RATIO OF THE INTEGRATED DEPOSITION DENSITIES OR OF THE TIME-INTEGRATED AIR CONCENTRATIONS OF ^{144}Ce and ^{90}Sr AT VARIOUS LOCATIONS

Location	*Period*	*Type of ratio*	$\Sigma^{144}Ce/\Sigma^{90}Sr$
Buenos Aires, Argentina	1966-1974	Deposition density	18.9
Moosonee, Canada	1963-1974	Air concentration	13.5
Antofagasta, Chile	1963-1974	Air concentration	12.8
Santiago, Chile	1963-1974	Air concentration	15.0
Puerto Mont, Chile	1963-1974	Air concentration	12.3
Lower Hutt, New Zealand	1968-1972	Deposition density	16.0
Chilton, United Kingdom	1961-1965	Deposition density	20.2
Chilton, United Kingdom	1967-1970	Deposition density	14.7
Sterling, United States	1963-1974	Air concentration	13.5
Miami, United States	1963-1974	Air concentration	14.2

120. The inhalation of ^{144}Ce gives rise to lung irradiation. At Moosonee (Canada) and Sterling and Miami (United States), the time-integrated concentrations of ^{144}Ce in air from 1963 to 1974 were 1.33, 1.78 and 1.66 pCi y m^{-3}, respectively, giving a mean of 1.6 pCi y m^{-3} (117). The time-integrated activity concentrations in air at Antofagasta and Santiago (Chile) for the same period were 0.36 and 0.39 pCi y m^{-3}, respectively, giving a mean of 0.38 pCi y m^{-3}. Assuming that these two means are representative of the northern and southern hemisphere, and using the ^{90}Sr integrated deposition data of table 2 to extrapolate the integrated air concentrations to cover the period 1954-1974, the resulting estimates for that period are respectively 3.0 and 0.7 pCi y m^{-3} for the northern and southern hemispheres.

121. Using the ICRP lung model (135, 136) with parameters of class Y, and assuming a mean particle size of 0.5 μm, which results in a 20-per-cent deposition in the pulmonary region of the lung, the transfer factor P_{15} (time-integrated air concentration-to-dose) is estimated to be 22 mrad per pCi y m^{-3}.

122. Applying this value of P_{15} to the time-integrated air concentrations given in paragraph 120 results in dose commitments to the lung of 65 and 15 mrad for the populations of the northern and southern temperate regions, respectively. The lung dose commitment to the world population is estimated to be about 38 mrad. Assuming a ^{144}Ce/^{90}Sr activity ratio of 48 at the time of fission, it can be estimated that the collective dose commitment to the lung per unit activity released is of the order of 0.3 man rad Ci^{-1}, for the past pattern of nuclear testing.

N. PLUTONIUM

1. Plutonium in the environment

123. Several isotopes of plutonium have been released into the environment by nuclear tests carried out in the atmosphere between 1945 and 1976. The most important, with half-lives shown in parentheses, are ^{239}Pu (24 000 y), ^{240}Pu (6600 y), ^{238}Pu (87 y) and ^{241}Pu (14 y). The last radionuclide is mainly a beta emitter and decays to the alpha emitter ^{241}Am (430 y). Since ^{239}Pu and ^{240}Pu are not usually distinguished in environmental activity measurements, reported ^{239}Pu activities should be assumed to apply to a mixture of ^{239}Pu and ^{240}Pu (116). Measurements have indicated that this mixture contains approximately 60 per cent of ^{239}Pu on an activity basis.

124. Plutonium released to the atmosphere during atmospheric tests is subsequently deposited on land and on the oceans as insoluble aerosol particles of the oxide. Profile measurements in sandy soil have shown that about 70 per cent is in the first 4-cm layer and virtually all in the top 30 cm (114). The profile depends on local climate and the physico-chemical properties of the soil. Other measurements (38) indicate that about 40 per cent of the plutonium is in the top 5 cm of soil.

125. The uptake of plutonium from soil by plants can be expressed as a concentration factor, usually defined as the ratio of the activity concentration in fresh plants to that in dry soil. Reported values for the plutonium concentration factor vary widely over the range $4\ 10^{-8}$ to $3\ 10^{-2}$, but representative values are on the average

of the order of 10^{-4} (38). From measurements of the ^{239}Pu intake and of the activity in the bone, muscle and liver of cows that had grazed on a contaminated range of the Nevada test site, a gastro-intestinal uptake factor of $3.4\ 10^{-5}$ was obtained (224). In similar study on the uptake of plutonium by reindeer that had fed on lichen, the uptake factor was found to be about $2.4\ 10^{-5}$ (128).

126. In the ocean, plutonium has moved to greater depths than has ^{90}Sr and ^{137}Cs. Noshkin *et al.* (193) found that 2-36 per cent of oceanic plutonium in the Atlantic Ocean was in the sediments. In the water, they found that about 50 per cent of the activity was below the thermocline. In 1964 the activity concentration of plutonium in the Pacific Ocean was about 10^{-4} pCi l^{-1} (202). Plutonium is taken up by marine biota, and the concentration factors for algae, plankton, crustacea are 1000-3000; for fish (muscle), 1-10 (192).

2. Levels in the environment

127. Most of the plutonium now dispersed around the world came from tests carried out prior to 1963; subsequent tests have contributed an additional 10 per cent to the global inventory (118). The deposition density rate and the integrated deposition density of ^{239}Pu-^{240}Pu can be inferred from the corresponding values for ^{90}Sr, as it has been observed that the Pu/^{90}Sr activity ratio in stratospheric- and surface-air samples has remained fairly constant in time with a value of about 0.017 (28, 116). A comparison of the cumulative deposit of Pu in soil with that of ^{90}Sr can also be used to estimate the global deposition of plutonium. From such measurements the global deposition of ^{239}Pu-^{240}Pu up to the end of 1973 is estimated to be 320 kCi, of which 250 kCi were in the northern hemisphere and 70 kCi in the southern hemisphere (116). This global deposition amounts to about 3 t of the ^{239}Pu isotope. In 1975 the stratospheric inventory in the northern hemisphere was less than 1 kCi (149).

128. Nuclear tests have contributed 9 kCi of ^{238}Pu to global fallout (116), while the re-entry of a satelite into the earth's atmosphere in 1964 contributed some 17 kCi, 70 per cent of which has deposited in the southern hemisphere, as discussed in the 1972 report of the Committee (245).

129. Although ^{239}Pu-^{240}Pu concentrations in ground-level air have been measured on a wide scale only since 1965, previous ^{239}Pu-^{240}Pu activity concentrations in air can be estimated from ^{90}Sr concentrations in air, assuming that the ^{239}Pu-^{240}Pu/^{90}Sr ratio has remained constant and that both nuclides have the same deposition velocity (149). Using this approach, Bennett found that the air activity concentration in New York reached a peak of about 1.7 fCi m^{-3} in 1963 and by 1972 had decreased to 0.031 fCi m^{-3} (22). The average deposition density rate of ^{239}Pu-^{240}Pu in New York for 1972-74 was 0.017 mCi km^{-2} y^{-1}, while the cumulative deposit density in 1974 was 2.68 mCi km^{-2} (38).

130. Bennett (32, 35) has reported results from a complete-diet sampling programme conducted in New York during 1972 and 1974, which showed an average annual dietary intake of 1.6 pCi of ^{239}Pu-^{240}Pu. Of the food groups analysed, grain products, and fruit and vegetables had the highest activity concentrations, both being about $5\ 10^{3}$ pCi kg^{-1}. It was also apparent from this study that external contamination of food is an important contributor to intake.

3. Pathways to man and dose commitments

131. Plutonium uptake and deposition in human tissues can follow the inhalation of airborne plutonium or the ingestion of contaminated food. The available data indicate that for plutonium released by atmospheric tests, the most important pathway to man is the inhalation of contaminated air. Dose commitments have been estimated for each pathway.

132. Bennett (28) has estimated that the cumulative intake by inhalation in New York from 1954 through 1975 was 43 pCi. As a single intake, this would have given rise to a body activity of 8.5 pCi, assuming a 20-per-cent retention factor as is indicated in the ICRP lung model (135, 136). But since the intake occurred over several years, allowing for loss of activity from the lung, the activity in the body was about 4 pCi at maximum in 1964, and for 1974 it was estimated to be 2.4 pCi (38).

133. The ^{239}Pu contents of various human organs measured at several areas of the United States in 1972 and 1973 in occupationally unexposed persons have recently been reported (12, 213). In this study, particular care was exercised in separating the lymph-node tissue, so that as little as possible of non-lymphatic tissue was included. These results are shown in table 21, together with the estimated values of

TABLE 21. CONCENTRATION OF PLUTONIUM IN BODY TISSUES OF NON-OCCUPATIONALLY EXPOSED PERSONS IN THE UNITED STATES, 1972-1973

(The number in parentheses is the number of samples)

(pCi kg^{-1})

	Lung	*Liver*	*Lymph node*	*Kidney*	*Vertebrae*
Los Alamos	0.36 (8)	0.72 (5)	16.0 (4)	0.09 (5)	0.72 (5)
Non-residents of Los Alamos	0.18 (17)	0.31 (10)	9.0 (15)	0.54 (10)	0.19 (16)
Colorado	0.31 (29)	0.81 (25)	6.8 (22)	1.4 (25)	0.50 (25)
Savannah River	0.18 (20)	0.54 (14)	18.0 (6)	1.0 (11)	0.31 (12)
Mean	0.27 (74)	0.68 (54)	11.0 (47)	0.68 (51)	0.31 (58)
Computed from fallout plutonium (1972)[a]	0.19	0.52	32.0	0.07	0.19

[a] Assuming organ weights for the lung, liver, lymph node and bone of 1.0, 1.7, 0.015 and 5.0 kg, respectively.

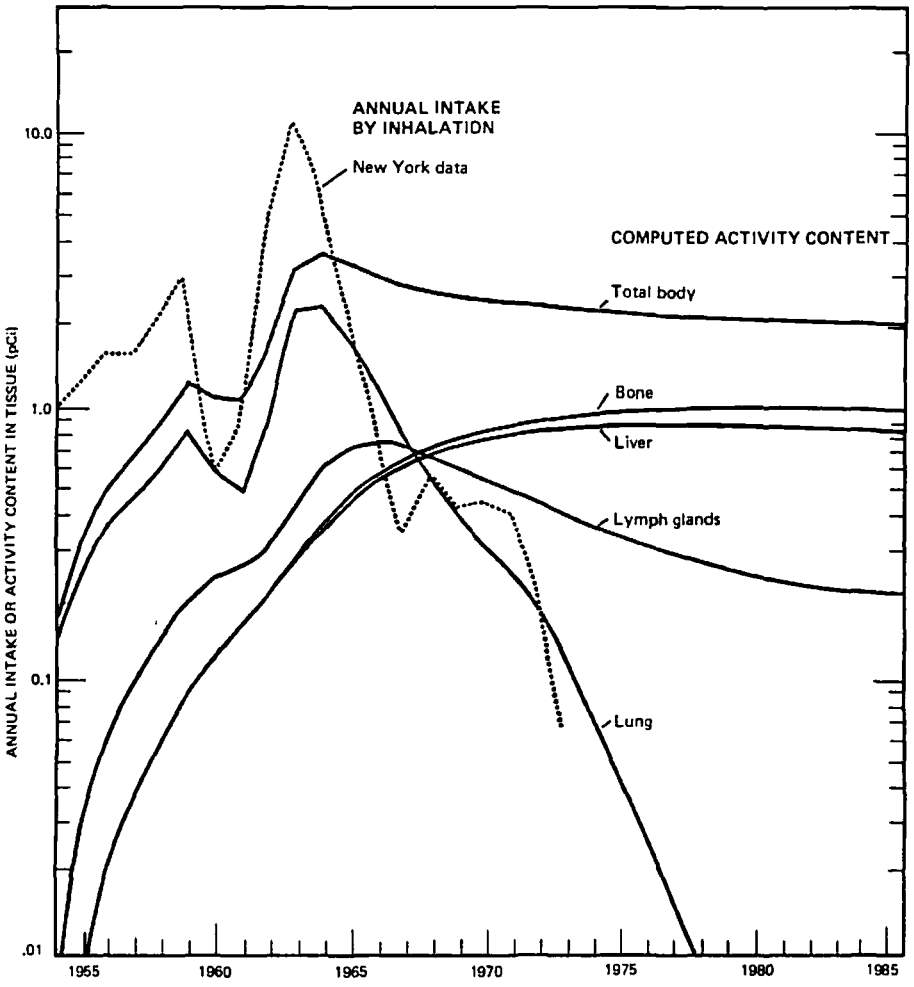


Figure XII. Annual ^{239}Pu inhalation intake (dotted curve) and computed activity content in human body tissues (solid curves)

Bennett based upon the New York data (28). The agreement is quite reasonable, considering the difficulties involved. It should be noted that, to get these results, Bennett used the ICRP lung model with class Y parameters (appropriate for insoluble aerosol particles), while the results with other classes of parameters were at variance with the measured values (28).

134. Inhalation of radioactivity resuspended from the soil surface by winds could add to the long-term intake due to airborne plutonium. Bennett (32), on the basis of natural ^{238}U concentrations in air and soil, considered that 10^{-9} m^{-1} would be a realistic estimate for the resuspension factor, applicable to activity in the top 1 cm of soil. This is in agreement with that estimated from normal dust loading of the atmosphere (6). This estimate is also in agreement with values determined using an artificial tracer in a lightly vegetated area (221). Using such a factor, resuspension would only contribute 0.5 per cent to the total integral activity of ^{239}Pu-^{240}Pu in air between 1954 and 2000 (29, 34). Since plutonium penetrates into the soil and thus becomes unavailable for resuspension, this effect is not expected therefore to contribute significantly to the dose commitment from plutonium.

135. By using estimates for the ^{239}Pu concentration in New York air between 1954 and 1972, assessed from ^{90}Sr deposition density data together with ^{90}Sr and ^{239}Pu concentration in air measured between 1965 and 1972, and utilizing the ICRP lung model (135, 136), Bennett has estimated the dose to man from inhalation of fallout ^{239}Pu through 2000 (28). The estimated ^{239}Pu annual intake and activity content in body tissues are shown in figure XII. The cumulative doses to 2000 are (mrad): lungs, 1.6; liver, 1.7; bone lining cells, 1.5. As the atmospheric inventory of ^{239}Pu decreases rapidly, the contribution from inhalation after 2000 is very small, and these cumulative doses are therefore good approximations of the dose commitments. The present estimate for the dose commitment to bone differs significantly from that given by the Committee in its 1972 report, which was based upon concentrations in surface air at Ispra, Italy, and on earlier values of parameters for the ICRP lung model (135, 136). It is also to be noted that the lung doses have been calculated on the basis of a uniform distribution of ^{239}Pu over the whole organ (28, 245). As plutonium particles are assumed to be insoluble, the actual distribution of doses in the lung is probably non-homogeneous, but the calculated value can be taken to represent the mean dose to the lung.

136. Assuming that the ^{239}Pu concentrations in New York air are representative of the whole 40°-50° latitude band, that the global distribution of ^{239}Pu deposition is the same as that for ^{90}Sr, and that the latitudinal distribution of the population remains unchanged, the

population-weighted dose through 2000 to the bone lining cells would be 1.0 mrad in the northern hemisphere and 0.3 mrad in the southern hemisphere.

137. For the purpose of estimating dose commitments from the ingestion of the plutonium mixture, two extreme cases will be considered, assuming in the first that the amount of plutonium transferred to food depends on the deposition density rate and in the second, that it depends on the cumulative deposit density.

138. Under the first assumption, P_{23} is estimated from the quotient 1.6 pCi y^{-1}/0.017 mCi km^{-2} y^{-1} to be 94 pCi per mCi km^{-2}. The total individual intake from plutonium deposited from all tests up to 1974 would be 94 pCi per mCi km^{-2} X 2.68 mCi km^{-2} = 252 pCi. Under the second assumption, on the other hand, the lifetime intake is estimated to be 1.6 pCi y^{-1} X 70 y = 112 pCi.

139. Of the ingested plutonium it is assumed that a fraction $3\ 10^{-5}$ is absorbed through the GI tract and that 45 per cent of this goes to the bone (136). For the two assumed cases of intake of 252 pCi and 112 pCi, the activity deposited in bone is $3.4\ 10^{-3}$ and $1.5\ 10^{-3}$ pCi, respectively.

140. The dose rate in bone per unit activity of plutonium is 0.098 mrad y^{-1} pCi^{-1} (28). Under the first assumed case, the activity in bone is $3.4\ 10^{-3}$ pCi, and the average exposure period in the population is 35 y. The dose commitment is therefore assessed to be $1.2\ 10^{-2}$ mrad.

141. Under the second assumed case the bone activity increases linearly with age with an average in the population of $1.5\ 10^{-3}$ pCi X 0.5 = $0.75\ 10^{-3}$ pCi. The factor of 0.5 takes account of the fact that the *per caput* bone activity is approximately 0.5 times that at death. The annual dose, averaged over all ages, is therefore 7.5×10^{-5} mrad. If it is assumed that the ^{239}Pu in the soil becomes unavailable only by decay, the dose commitment is estimated to be 2.6 mrad.

142. Taking into account population distribution and using the procedures outlined in Annex A, the collective dose commitments to the lung and to bone lining cells, per unit activity released by past nuclear explosions, are of the order of 10 man rad Ci^{-1}.

III. EXTERNAL IRRADIATION

143. Many radionuclides present in fallout emit gamma rays and contribute to the dose from external irradiation. The most important from this point of view are a number of short-lived radionuclides, the most significant of which are ^{95}Zr and its daughter ^{95}Nb, and the long-lived ^{137}Cs.

144. In principle, it is possible to calculate the external doses from the integrated deposition density of each radionuclide. Table 22 shows the conversion factors for estimating absorbed dose in air, 1 m above ground, that were used in the 1972 report and which are based largely on the work of Beck *et al.* (15). For short-lived radionuclides, a plane source on the surface of the ground is postulated, but for ^{137}Cs an exponential profile is assumed with a mean depth of 3 cm.

TABLE 22. CONVERSION FACTORS FOR THE ASSESSMENT OF ABSORBED DOSES IN AIR 1 m ABOVE GROUND

	^{95}Zr	^{103}Ru	^{106}Ru	^{137}Cs	^{140}Ba	^{141}Ce	^{144}Ce
Dose-rate conversion factor (mrad y^{-1} per mCi km^{-2})	0.341[a]	0.072	0.042[a]	0.033	0.316[a]	0.011	0.004[a]
Mean life (y)	0.257	0.157	1.44	43.7	0.051	0.129	1.13
Dose conversion factor (mrad per mCi km^{-2})	0.087	0.011	0.060	1.44	0.016	0.0014	0.0045

Note: A plane source on the ground surface is assumed except for ^{137} Cs, for which the source is assumed to be exponentially distributed with a mean depth of 3 cm.

[a] Including contributions from the daughter radionuclides, assumed in transient equilibrium.

145. The assessment of organ doses from absorbed doses in air is discussed in Annex A. A combined factor of 0.8 is used in this report to account for the change of material (air to tissue) and for back-scatter and shielding afforded by other tissues of the body. The estimation of the organ doses from external radiation due to fallout require the use of a further factor representing the shielding effect of buildings. This shielding is taken to reduce the absorbed dose rate in air in the building, on average, to 20 per cent of its outdoor value. Assuming that on the average 80 per cent of the time is spent indoors, the effective shielding factor of the building is 0.4 (241, 245).

146. The overall factor used in this report to convert air absorbed doses to organ doses is therefore 0.8 X 0.4 = 0.32. Transfer factors P_{25} relating integrated depositions of selected gamma-emitting nuclides to the resulting doses in the tissues of interest to the Committee can be calculated by multiplying the conversion factors shown in table 22 by 0.32.

A. SHORT-LIVED RADIONUCLIDES

147. Although the deposition of short-lived radionuclides has not been measured over the whole period during which nuclear tests were conducted, there are sufficient data available to estimate approximately the mean integrated deposition density. This estimation is based on the use of ratios of the time-integrated air concentrations and of integrated deposition densities of the relevant nuclides, assessed from measurements at a

number of sites, and the known latitudinal distribution of the integrated deposition densities of some nuclides, such as ^{90}Sr.

148. The integrated deposition density of ^{144}Ce has been estimated by this procedure in previous sections of this Annex and is shown in table 20. In paragraph 89 it was noted that the $^{106}Ru/^{144}Ce$ activity ratio changes slowly with time and was estimated to be 0.5 during the period of deposition.

149. From the estimated values of the integrated deposition density of ^{144}Ce and ^{106}Ru and the conversion factors of table 22 multiplied by 0.32 (para. 146) it is possible to assess the dose commitment from these nuclides (see table 25).

150. The activity of a number of fission products in air has been monitored at sites varying in latitude in the vicinity of the meridian 80°W since 1963 (117). The ratio of the time-integrated air activity of ^{95}Zr to that of ^{90}Sr for the period 1966-1974 is plotted as a function of latitude in figure XIII. By 1966 there was probably very little ^{95}Zr activity left from tests prior to 1963. The deposition density of ^{95}Zr in each latitude band in the period 1966-1973 was estimated from the corresponding data for ^{90}Sr for the same period, using ratios taken from figure XIII. The results are shown in table 23 (117).

TABLE 23. LATITUDINAL DISTRIBUTION OF ^{95}Zr INTEGRATED DEPOSITION DENSITY, 1966-1973

Latitude band	*Area of band (10^6 km^2)*	*Relative population of band (%)*	*Integrated deposition density of ^{95}Zr (mCi km^{-2})*
70°-80°N	11.6	0.0	8
60°-70°N	18.9	0.4	28
50°-60°N	25.6	12.2	61
40°-50°N	31.5	13.8	64
30°-40°N	36.4	18.2	59
20°-30°N	40.2	29.2	49
10°-20°N	42.8	9.8	27
0°-10°N	44.1	5.6	32
0°-10°S	44.1	5.8	98
10°-20°S	42.8	1.8	137
20°-30°S	40.2	1.6	195
30°-40°S	36.4	1.4	147
40°-50°S	31.5	0.1	105
50°-60°S	25.6	0.05	23

Source: Reference 155.

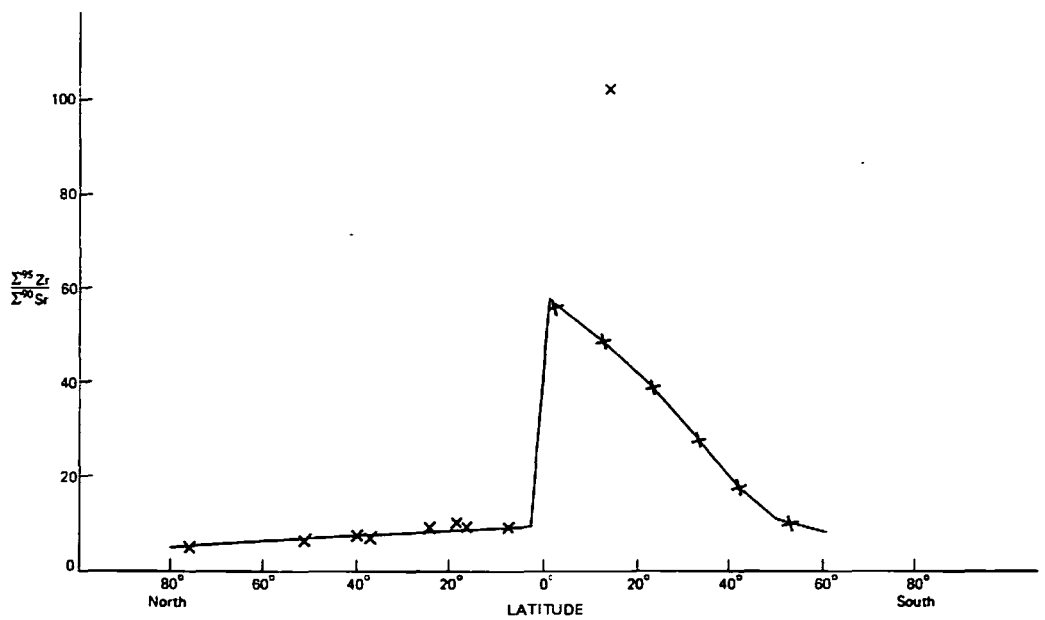


Figure XIII. Latitudinal variation of the ratio of time-integrated air concentrations of ^{95}Zr and ^{90}Sr for the period 1966-1974

151. There are few data on the global deposition of ^{95}Zr prior to 1963, and it is probably in this period that the greatest deposition occurred in the northern hemisphere. It is possible to estimate the ^{95}Zr integrated deposition density from that of ^{89}Sr if some reliable estimate for their ratio could be made. The $^{95}Zr/^{89}Sr$ ratio only changes with a half-time of about 200 d owing to radioactive decay. The ratio of the time-integrated air concentrations $\Sigma^{95}Zr/\Sigma^{89}Sr$ in 1963 at Thule (Greenland), Moosonee (Canada), Sterling and Miami (United States) were 2.3, 2.7, 2.9 and 3.0, respectively, with a mean of 2.7 (117). The mean ratio at seven northern hemisphere sites in 1962 was 1.5 (60, 115, 242). The northern hemisphere deposition of ^{89}Sr in 1962 and 1963 of 27 and 15 MCi respectively, reported by Hardy (111), leads to a weighted mean of 1.93 for the integrated concentration ratio $\Sigma^{95}Zr/\Sigma^{89}Sr$.

152. Between 1961 and 1969 the deposition density of ^{89}Sr in the 40°-50°N latitude band was 346 mCi km^{-2} (111). Using the ^{90}Sr deposition data given in table 2 as a guide, the ^{89}Sr deposition density in this zone up to 1966 is estimated to be 477 mCi km^{-2} in the northern hemisphere and 57 mCi km^{-2} for the same zone in the southern hemisphere. The ^{95}Zr deposition densities in the northern and southern 40°-50° zones up to 1966 are estimated as 920 and 110 mCi km^{-2} respectively, using the $\Sigma^{95}Zr/\Sigma^{89}Sr$ ratio of 1.93 given in paragraph 151. Adding to these numbers the corresponding values for the period 1966-1974 from table 3, the estimated ^{95}Zr deposition densities up to the end of 1973 are 984 and 214 mCi km^{-2} for the northern and southern 40°-50° zones, respectively. The population-weighted global average ^{95}Zr deposition density is estimated, using the ^{90}Sr data as a guide, to be 650 mCi km^{-2}.

TABLE 24. RATIO OF THE INTEGRATED DEPOSITION DENSITIES OR OF THE TIME-INTEGRATED AIR CONCENTRATIONS OF ^{103}Ru, ^{141}Ce, ^{140}Ba and ^{95}Zr AT VARIOUS LOCATIONS AND TIMES

Location	*Period*	*Type of ratio*	$\frac{\Sigma^{103}Ru}{\Sigma^{95}Zr}$	$\frac{\Sigma^{141}Ce}{\Sigma^{95}Zr}$	$\frac{\Sigma^{140}Ba}{\Sigma^{95}Zr}$
Buenos Aires, Argentina	1966-1974	Deposition density	0.72	–	0.92
Pretoria, South Africa	1966-1973	Air concentration	0.88	–	0.89
Stockholm, Sweden	1969-1972	Air concentration	–	0.19	0.52
Chilton, United Kingdom	1961-1964	Deposition density	–	–	0.63
Chilton, United Kingdom	1967-1970	Deposition density	0.66	0.53	0.46
Pittsburg, United States	1961-1963	Deposition density	–	0.93	0.26
		Average	0.75	0.55	0.62

153. It is possible to estimate the dose commitment from ^{103}Ru, ^{141}Ce and ^{140}Ba from the calculated ^{95}Zr integrated deposition density. Table 24 gives the ratios of the integrated air concentrations or integrated depositions of these radionuclides to that for ^{95}Zr for several sites and periods of time. If F_j is the integrated deposition density of radionuclide j and K_j is the conversion factor of table 22 multiplied by 0.32 (para. 146), the total external dose commitment can be expressed as

$$D^c = \sum_j K_j F_j = K_a F_a + F_a \sum_{j \neq a} K_j \frac{F_j}{F_a} \qquad (13)$$

and therefore

$$D = K_a^* F_a \qquad (14)$$

where K_a^*, the effective P_{25} factor for nuclide a, is defined by

$$K_a^* = K_a + \sum_{j \neq a} K_j \frac{F_j}{F_a} \qquad (15)$$

154. In this way the dose commitment from a group of radionuclides can be estimated from the integrated deposition density of a given radionuclide a. The effective P_{25} factor for computing the dose commitment due to ^{95}Zr, ^{103}Ru, ^{141}Ce and ^{140}Ba from the ^{95}Zr deposition density was determined using equation 15 together with the integrated activity ratios of table 24 and the conversion factors of table 22 multiplied by 0.32 (para. 146). The estimated value of this effective conversion factor is 0.034 mrad per mCi km^{-2}, with upper and lower limits of 0.04 and 0.03 mrad per mCi km^{-2}, respectively, obtained by using the largest and smallest ratios shown in table 24.

155. The combined dose commitments from ^{95}Zr, ^{103}Ru, ^{141}Ce and ^{140}Ba, calculated using this effective P_{25} factor and the estimated ^{95}Zr integrated deposition density given in paragraph 152, is shown in table 25, which also shows the total dose commitment from short-lived radionuclides.

TABLE 25. DOSE COMMITMENT DUE TO EXTERNAL RADIATION FROM SHORT-LIVED RADIONUCLIDES

(mrad)

Radionuclide	*Northern temperate zone*	*Southern temperate zone*	*Global (population-weighted)*
^{144}Ce	1.8	0.5	1.0
^{106}Ru	12	3.5	7.3
$^{95}Zr + {}^{103}Ru + {}^{141}Ce + {}^{140}Ba$	34	7.4	22
Total	48	11	30

Note: These estimates include a factor of 0.32 to allow for body screening and average shielding from buildings.

156. It is interesting to compare the estimated values of table 25 with actual determinations of the external dose in both hemispheres. At Chilton in the United Kingdom the total gamma absorbed dose in air from fallout has been determined by a combined procedure including direct measurements and computation from measured depositions (61). The estimate, for the period 1951 to 1973, is 137.7 mrad; the contribution from ^{137}Cs is estimated as 33.3 mrad, so that the contribution from short-lived radionuclides is 104.4 mrad. The corresponding tissue dose (applying the factor 0.32) is 33 mrad. In the southern hemisphere, for Buenos Aires up to 1975, a tissue dose of 15 mrad has been estimated (19, 20, 166, 167), based upon direct calculation from measured deposition densities of individual short-lived fission products.

B. CAESIUM-137

157. The integrated deposition density of ^{137}Cs from all tests was given in paragraph 115. Using this information and the conversion factor for caesium from table 22, multiplied by 0.32 (para. 146), the dose commitment to body tissue is estimated to be (mrad): northern temperate zone, 62; southern temperate zone, 18; world population, 38.

C. TOTAL DOSE COMMITMENT FROM EXTERNAL IRRADIATION

158. The global dose commitment from external irradiation is estimated to be 68 mrad, the combined short-lived nuclides and ^{137}Cs contributing each about half of this value. As ^{137}Cs released in nuclear detonations is accompanied by a given proportion of short-lived products, it is possible to assess the collective dose commitment from external exposure normalized to unit activity of ^{137}Cs released. The value calculated by the procedures indicated in Annex A is of the order of 10 man rad Ci^{-1}.

IV. SUMMARY OF DOSES AND DOSE COMMITMENTS FROM NUCLEAR EXPLOSIONS

159. It is difficult to summarize the doses for the whole world population from nuclear test explosions because they arise from a variety of radionuclides which differ widely in their behaviour in the environment and in their dosimetric characteristics. To state current annual doses would reveal only a small part of an exposure situation,

which is known to vary not only with time, but also with geographical location, living conditions and age. For a given group of individuals, for whom these factors are known, the annual doses from external and internal exposures may be presented as a function of age for some selected organs and tissues of interest; that would give a full picture of the annual doses for the particular groups. For some long-lived radionuclides that are globally distributed, such as ^{137}Cs, this information may be derived for the whole world population as *per caput* annual doses which would be representative of individuals irrespective of age and location. For other radionuclides, however, the individual annual doses will vary substantially with location and age. That is the case with short-lived radionuclides, such as ^{131}I, ^{131}I, as regards location, and with bone-seeking radionuclides, such as ^{90}Sr, as regards age. Even for these radionuclides, however, once the population group of interest has been identified, it is possible to describe the current and expected exposure situations for the individuals involved, drawing on the information given in the various sections of this Annex.

160. If the variation of individual organ dose rates with time were known for all locations, living conditions and ages, a world population *per caput* dose rate could be calculated. Its integral over infinite time would be the global dose commitment from the nuclear explosions to date. Using the methods described in this Annex, however, this integral can be evaluated even though the *per caput* dose rate as a function of time is not known or is difficult to derive. Because the global dose commitment, as described in Annex A, can be used as a relative measure of the detriment, the Committee, as in previous reports, has found this quantity to be a useful single measure of the irradiation consequences for the whole world population. It is therefore summarized in table 26.

TABLE 26. SUMMARY OF DOSE COMMITMENT FROM RADIONUCLIDES PRODUCED IN ALL NUCLEAR TESTS CARRIED OUT BEFORE 1976

(mrad)

	Northern temperate zone				*Southern temperate zone*				*World population*			
Source of radiation	*Gonads*	*Bone marrow*	*Bone lining cells*	*Lung*	*Gonads*	*Bone marrow*	*Bone lining cells*	*Lung*	*Gonads*	*Bone marrow*	*Bone lining cells*	*Lung*
External												
Short-lived nuclides	48	48	48	48	11	11	11	11	30	30	30	30
^{137}Cs	62	62	62	62	18	18	18	18	38	38	38	38
Internal												
^{3}H	2	2	2	2	0.2	0.2	0.2	0.2	2	2	2	2
^{14}C[a]	7	32	29	9	7	32	29	9	7	32	29	9
^{54}Mn				1								1
^{55}Fe	1	0.6	1	1	0.3	0.2	0.3	0.3	0.7	0.4	0.7	0.7
^{90}Sr		84	120			24	33			52	71	
^{89}Sr		0.4								0.3		
^{106}Ru				41				10				24
^{137}Cs	27	27	27	27	8	8	8	8	17	17	17	17
^{144}Ce				65				15				38
^{239}Pu[b]			1	1			0.3	0.3			0.9	0.9
Total[c]	150	260	290	260	45	93	100	72	94	170	190	160

Notes: 1. The dose commitments for ^{85}Kr, ^{136}Cs and ^{140}Ba, although discussed in the text, are not shown in this table because they are negligible compared with the values included.

2. For internal irradiation, where body activities have been measured, uncertainties are probably within a factor of 2. For external irradiation and for lung-dose estimates, where the models used were not checked by direct measurement, the uncertainties are probably within a factor of 5.

[a] Dose accumulated up to the year 2000. The total dose commitment to gonads and lung is about 120 mrad, to bone lining cells 414 mrad and to bone marrow 455 mrad, delivered over some 8300 y.

[b] These dose commitments appear to be the same in different organs because of rounding. Only inhalation contributions are shown; for discussion on the ingestion pathway see chapter II, section N.

[c] Rounded to two significant figures.

161. The values shown in table 26, taken from the relevant paragraphs in the preceding sections, have been rounded off. For this reason, when the differences between the estimated organ dose commitments are small, the table gives the appearance of a uniform dose over several organs. In the case of doses from external gamma radiation, or from internal emitters that are homogeneously distributed in the body, such as ^{3}H and ^{137}Cs, the dose commitment is essentially the same for all the relevant organs of the body.

162. The methods for calculating the values of the dose commitments given in table 26 have been reassessed since the 1972 report of the Committee. In some cases, particularly for short-lived nuclides and ^{90}Sr, this reassessment has produced dose commitment estimates that differ significantly from those given in the 1972 report.

163. For the radionuclides listed in table 26, the irradiation to which the world population was committed by nuclear tests up to 1975 is already largely completed for all except ^{137}Cs (external and internal), ^{3}H, ^{14}C, ^{90}Sr and ^{239}Pu. Therefore, in terms of current annual doses, only these five nuclides need to be considered. Caesium-137 makes major contributions for

all body tissues which are essentially independent of age; whereas the further substantial contribution from ^{90}Sr in bone marrow and bone lining cells is strongly dependent on age. In comparison, the contributions of ^{3}H, ^{14}C and ^{239}Pu to current annual doses are very small.

164. Although ^{137}Cs and ^{90}Sr are the only substantial contributors to current annual doses to the body organs and tissues included in table 26, it is not possible to summarize this annual dose situation in a simple description for the whole world population. It may be helpful, however, to indicate the magnitude of the annual doses in 1975 using ^{137}Cs as an illustrative example. Whole-body contents of ^{137}Cs in 1975 (table 19) ranged from 8 to 29 pCi $(gK)^{-1}$, which would have caused annual doses to body tissues in the range 0.1-0.5 mrad. The external exposure from ^{137}Cs deposition in soil would have added less than 0.2 mrad to these doses. Because of the long half-life of ^{137}Cs, the world population is committed to continued exposure from this radionuclide for many years. This accounts for the substantial contribution of ^{137}Cs to the dose commitment.

165. For nuclear tests carried out in the atmosphere in the northern and southern hemispheres since the Committee's 1972 report, ^{131}I in milk supplies has led to irradiation of the thyroid glands of exposed populations in the periods immediately following the tests. Doses due to ^{131}I in infant thyroids–the most highly exposed organ–ranged up to 15 mrad in the northern hemisphere in 1974 and 1976, whereas, in the southern hemisphere, doses to infant thyroid ranged up to about 100 mrad in 1973 and up to some hundreds of mrad in 1974.

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