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NOTE

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

ANNEXES

Annex A

RADIO-ACTIVE CONTAMINATION OF THE ENVIRONMENT BY NUCLEAR TESTS

CONTENTS

I. Introduction

1. Debris from nuclear tests in the atmosphere is still the major radio-active man-made contaminant of the environment. By comparison, the gaseous and liquid wastes presently discharged in limited amounts into the environment from reactors and fuel reprocessing plants and by industrial, medical or research applications of radio-isotopes contribute much less to radio-active contamination and will not be considered in this report.

2. Although several nuclear devices have been tested since the last report of the Committee,[1] these have not added significantly to the global inventory of long-lived radio-active material in the biosphere. Furthermore, since the last report was prepared (June 1966), the rate of deposition of nuclear debris from the atmosphere has decreased substantially, thereby simplifying considerably the problem of predicting the future levels of the long-lived radio-nuclides in the food and tissues of man to be expected from tests carried out so far.

3. Moreover, the results of extensive and comprehensive surveys carried out in a number of countries have contributed considerably to our knowledge of the levels of long-lived radio-nuclides in man and food chains in those countries, as well as to our understanding of the many and complex processes involved in the transfer of radio-activity to the human body.

4. In the present report, the impact of these recent developments on the assessment of the effect of nuclear fall-out on man is reviewed in detail. In particular, the radiation doses to which man has been committed are estimated from the results of the series of measurements now available.

5. Although the estimates of the doses thus obtained do not differ significantly from the previous ones, the Committee now has increased confidence that they are representative of the doses to which humans have been committed, at least for those populations in the countries and areas from which the results of measurements are available.

II. Recent data on environmental contamination

A. Airborne and deposited artificial radio-activity

1. *Atmospheric injections*

6. Six nuclear devices were exploded above ground in central Asia during the years 1966-1968. After each test in 1966 and 1967, increases in surface-air activity were observed in Japan within a few days,[2-7] and in North America[8-11] and Europe[12, 13] within the first two weeks. The debris from the explosion in June 1967, on the other hand, was observed at the surface after some months. Reports describing the behaviour of the debris from the 1968 test are not yet available.

7. Five nuclear devices were exploded above ground at the Tuamotu Islands in the south Pacific during the last half of 1966, three in mid-1967 and five between July and September 1968. Increased surface activities were observed in South America,[14, 15] South Africa,[12, 13, 16] Australia[17-22] and New Zealand[23-25] within a month after each explosion.

8. Temporarily increased surface-air activities have been observed from time to time. The composition of the radio-active material suggests that it has originated from underground explosions.[26-28]

9. In January 1968, an airplane carrying nuclear weapons crashed on the ice in a sparsely populated area near Thule off the coast of northern Greenland. Most of the radio-active material, mainly consisting of plutonium-239, was spread over an area of approximately 12,000 m^2. There was no nuclear explosion and no evidence was found that radio-activity had spread from the immediate vicinity of the place of accident.[29]

2. *Inventories*

(a) *Strontium-90 and caesium-137*

10. No significant amounts of nuclear debris were injected into the atmosphere between 1963 and mid-1967, and the stratospheric content of long-lived nuclides has consequently decreased steadily. Thus, in the period 1963-1966, the total content of strontium-90 in the atmosphere decreased at an approximately constant rate with an apparent half-life of about one year.[30, 31] The same half-life was found for the manganese-54 presumably produced in the 1961 and 1962 test series presumably produced in the 1961 and 1962 altitudes in 1962 showed a somewhat smaller rate of removal with a half-life of about 17.5 months. It is estimated that the explosions in 1967 added 170 kilocuries and 0.6 kilocuries of strontium-90 to the stratosphere of the northern and southern hemispheres, respectively, while those in 1968 added a further 160 kilocuries and 240 kilocuries[32, 33] (figure 1). Because of the small amount of debris from earlier tests still remaining in the stratosphere in 1968, these recent additions have increased the stratospheric inventory by about 50 per cent. However, they have only added an amount equal to about 4 per cent of the global inventory (deposited plus stratospheric) due to the earlier tests.

11. The $^{137}Cs/^{90}Sr$ ratio in nuclear debris may vary to some extent, depending not only upon the particular processes taking place in the nuclear devices but also upon fractionation phenomena. However, observations on the $^{137}Cs/^{90}Sr$ ratio in atmosphere and deposit in the years 1966-1968 have not revealed any systematic trend, and, for the purposes of estimating global inventories, it can be assumed that its value is 1.6.[12, 13, 34-36]

(b) *Carbon-14*

12. The content of artificially produced carbon-14 in the stratosphere decreased from (36 ± 8) 10^{27} atoms at the beginning of 1963 to (17 ± 4) 10^{27} atoms at the beginning of 1965.[37] No recent data on the stratospheric content in the southern hemisphere are available, but the indications are that the decrease has been small since 1965. The tropospheric content of carbon-14 in the northern hemisphere has gradually decreased since the years 1963-1964, when maximum concentrations of about 100 per cent of the natural level were observed, to about 65 per cent in 1967.[38] In the southern hemisphere, the concentration has gradually increased as a consequence of interhemispheric mixing so that the tropospheric concentrations were about the same in both hemispheres in 1967.[38] No observations on the effect of the explosions in 1967 and 1968 on the carbon-14 levels have been reported.

(c) *Plutonium-238*

13. The burn-up of the radio-isotope power source SNAP-9A in the upper atmosphere in April 1964 released 17 kilocuries of plutonium-238.[39, 40] Because of the high altitude of injection and the small particle size of the debris, the rate of depletion of the upper stratosphere was small during the first years, the apparent half-life being about ten years.[41] The rate of

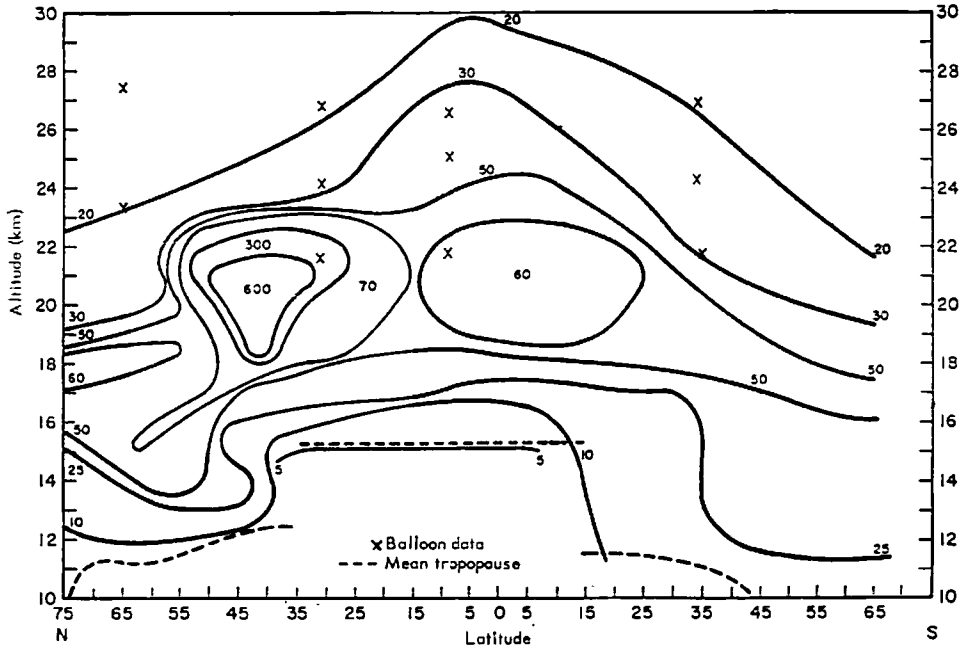


Figure 1. ^{90}Sr concentration contours, August 1967[32] (pCi (100 scm)$^{-1}$, where 1 scm = 1.226 kg air)

depletion has gradually increased, and the apparent half-life in the stratosphere after 1966 has been estimated to be between two and three years.[42, 43] Measured upper-air concentrations accounted for about 3 kilocuries in the northern hemisphere and 8 kilocuries in the southern hemisphere in mid-1967,[42] and the cumulative deposit to the end of 1967 was estimated to be 2.2 kilocuries and 4.7 kilocuries in the northern hemispheres, respectively.[43]

3. *Deposition*

(a) *General*

14. In the period 1965-1967, the annual deposition of strontium-90 decreased by about 50 per cent per year in the northern hemisphere and by a somewhat smaller amount in the southern hemisphere.[13, 44] The latitudinal variation was, in general, the same as earlier, with the highest deposition in the middle latitudes of each hemisphere (figure 2). In the northern hemisphere, a pronounced seasonal variation with maxima in spring was observed throughout the period (figures 3 and 4). A similar but less pronounced variation was also observed in the southern hemisphere.

15. Most of the strontium-90 and caesium-137 deposited up to the middle of 1967 was due to explosions occurring before 1963. In the second half of 1967, steadily increasing $^{144}Ce/^{137}Cs$ ratios in the northern hemisphere indicated that a larger part of the long-lived nuclides came from recent explosions.[13] It has been estimated that about half of the long-lived nuclides deposited in the northern hemisphere in 1968 came from recent explosions.[13]

16. The nuclear atmospheric explosions occurring between 1966 and 1968 have all resulted in deposition of short-lived fission products. A study by Hardy[45] on $^{89}Sr/^{90}Sr$ ratios in deposition indicates that most of the deposition occurring within the first half-year after an explosion is deposited in the hemisphere where the explosion took place. However, small amounts of fresh debris from explosions in the southern hemisphere have occasionally been observed in the northern hemisphere and vice versa.[13, 45, 46]

17. Fresh nuclear debris consists of a mixture of a large number of beta- and gamma-emitting nuclides. The composition changes with time and may also be affected by fractionation of the debris. The total beta activity or the amount of any single nuclide will, for that reason, not give a quantitative measure of the deposit occurring soon after an explosion. However, the content of barium-140 in ground-level air or precipitation can be used as a convenient indicator of the amount of fresh deposit, as it can easily be measured by gamma-spectrometric methods and also because it has a half-life of the same order of magnitude as iodine-131, which is the nuclide of main concern as regards doses from fresh deposit. Debris from the explosions in central Asia has normally been observed at ground level in the northern hemisphere during the first month after explosion.[13, 45] The levels have been moderate, peak values of barium-140 observed in the United Kingdom between 1966 and 1968 ranging from 0.01 to 0.1 pCi kg^{-1} in ground-level air. The ground-level activities in the southern hemisphere due to the explosions in the south Pacific have shown barium-140 peak values of about 1 pCi kg^{-1} in South Africa,[13] Australia[19] and Argentina.[15] Occasional high total beta activities in ground-level air have been observed in Japan[5-7] and North America.[9]

18. The global annual deposition of strontium-90 has been estimated from the results of two worldwide networks operated by the United Kingdom Atomic Energy Research Establishment (AERE) and the United States Atomic Energy Commission Health and Safety Laboratory (HASL). Statistical analysis of deposition data indicated that the latter network had underestimated the deposition by as much as 20 per cent,[47] and this has now been confirmed.[48, 49] The cumulative global deposition at the end of 1966 was, from the AERE network, 12.5 megacuries[48] and, after allowing for the collection efficiency of the samplers, 12.6 megacuries[48] from the other network.

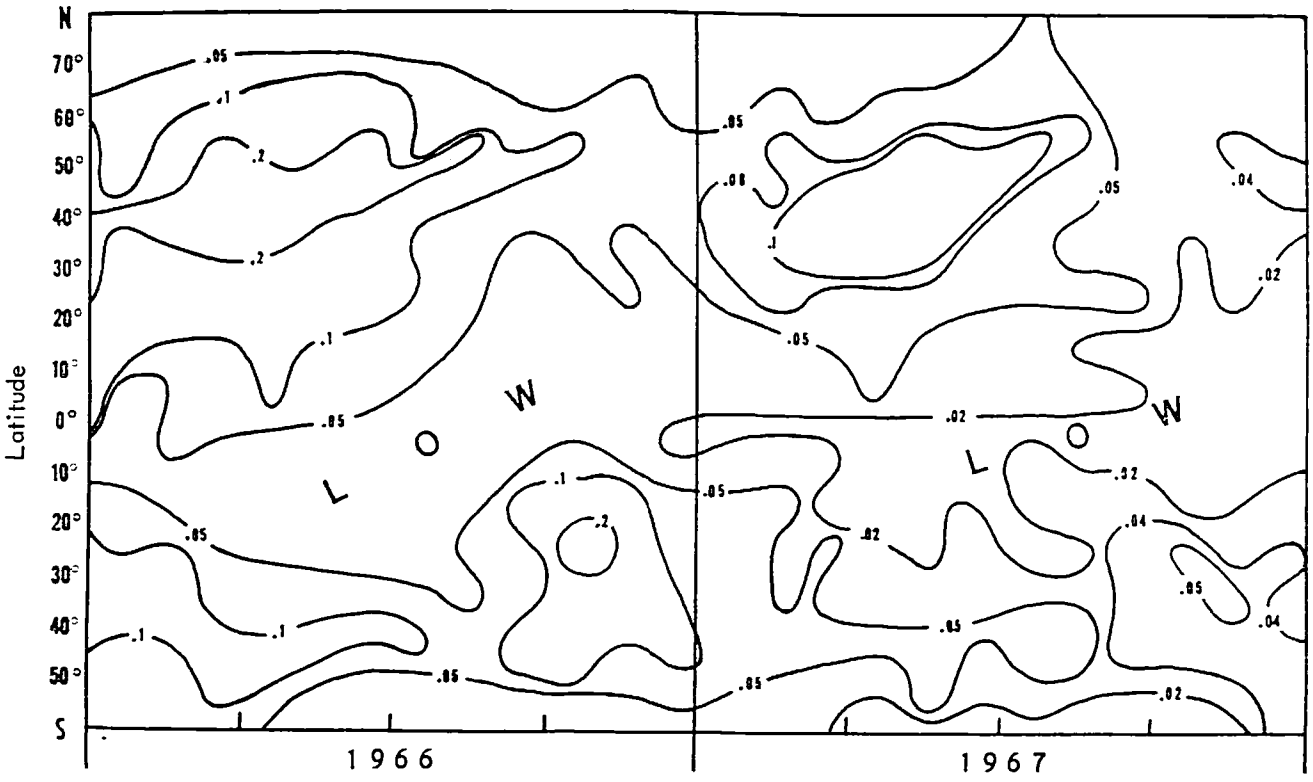


Figure 2. Monthly zonal average deposition of ^{90}Sr by latitude and time, 1966-1967[44] (mCi km^{-2} per month)

19. The cumulative deposit has been independently estimated from the results of a world-wide sampling programme of strontium-90 contents of soils[50] to be 13 megacuries. The cumulative deposits from 1958 to 1967 are given in figures 5 and 6 and table I. Table II summarizes the strontium-90 inventory from 1963 to 1967, as derived from upper-air and deposition data.

20. No comprehensive information on global caesium-137 deposition comparable to that on strontium-90 is available. For most practical purposes, it is sufficient to assume a constant $^{137}Cs/^{90}Sr$ ratio and so calculate the caesium-137 deposition from the deposition of strontium-90. The value of the ratio to be used for estimating global inventories of caesium-137 was discussed in paragraph 11.

(b) *Relative deposition on land and ocean*

21. Deposition in the oceans was discussed in detail in the Committee's 1966 report.[51] The main concern in this connexion was that large differences in deposition rates between oceans and land could, if unrecognized, give rise to significant errors in the estimates of the global inventory. Although this did not directly affect estimates of the dose commitments to the world's

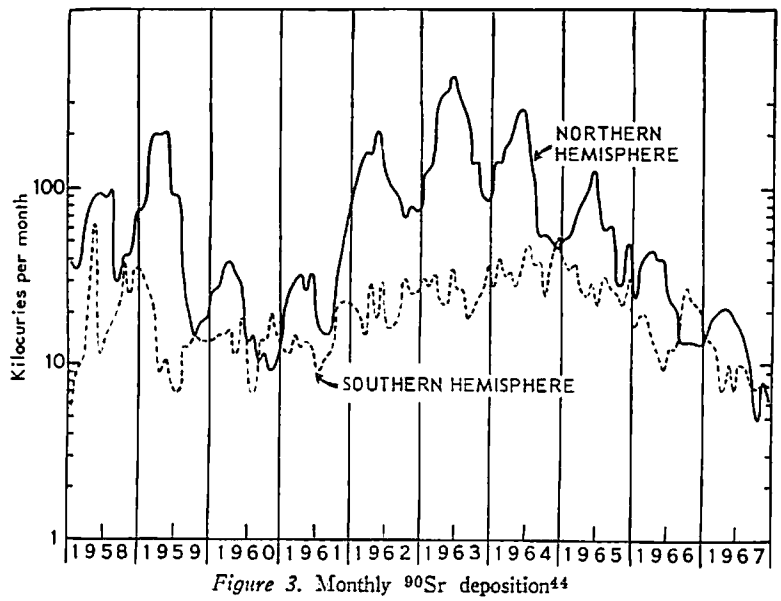


Figure 3. Monthly ^{90}Sr deposition[44]

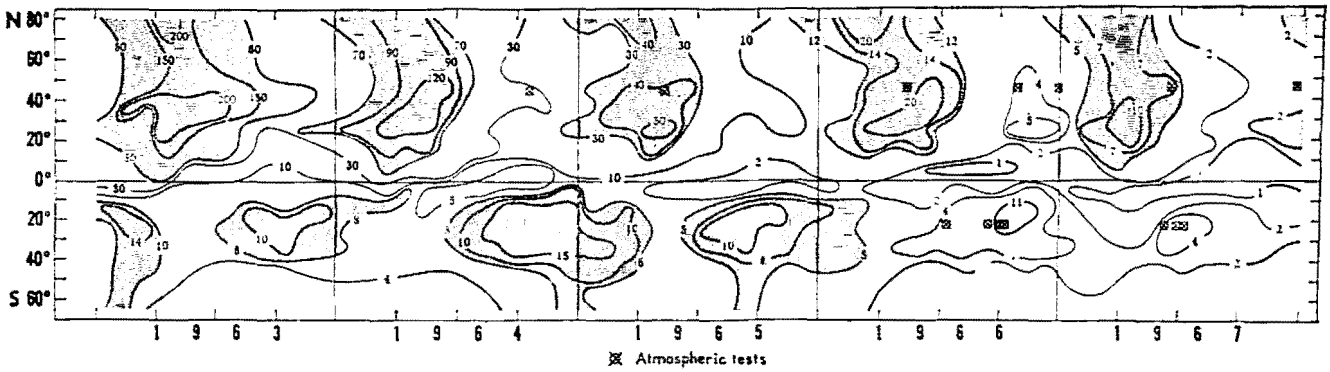


Figure 4. ^{90}Sr concentrations in surface air based on observations made between 35°W and 155°W[115] (dpm per 1,000 scm, where 1 scm = 1.226 kg air)

population, it was felt that the possibility of large systematic errors in assessing the inventory needed to be studied closely. The experimental data on this subject are still somewhat contradictory.

22. The evidence for excess strontium-90 fall-out in the oceans comes primarily from the sea-water measurements themselves which, when integrated over the entire volume of the oceans, result in an estimate of the inventory substantially larger than that extrapolated from land measurements. Systematic observations of strontium-90 concentrations in surface water of the north Atlantic have also suggested that the rate of deposition there is higher than over land.[52, 53]

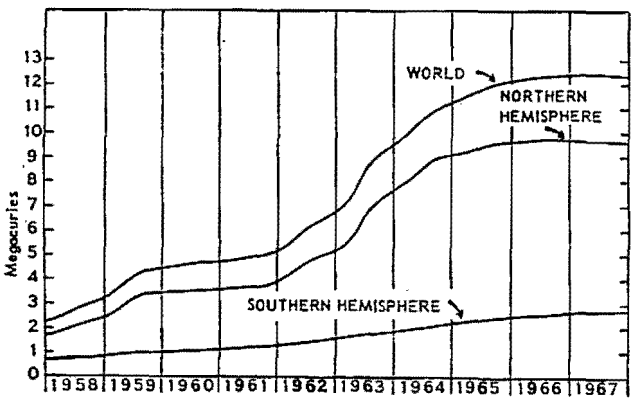


Figure 5. Cumulative ^{90}Sr deposits[44]

23. However, the possibility of large differences between land and ocean deposition is unlikely because of other considerations. The most compelling is that the estimates of the global strontium-90 inventory,[54] when corrected for radio-active decay, have been virtually constant during the period 1963-1967 (table II). As the estimates of the deposit were based on measurements made at land stations, a considerably higher deposition onto the oceans should have resulted in systematically decreasing estimates of the total inventory.

24. Studies of the cumulative deposit of strontium-90 onto ocean shores in Norway and Iceland[55] also fail to show any significant difference between the deposit close to the sea and some kilometres inland. In addition, an experiment carried out at Crater Lake, Oregon, United States, showed that there was no measurable difference in strontium-90 deposition onto a fresh-water surface of about 60 km^2 compared to that onto adjacent land.[56] These results suggest that, if there is enhanced deposition of strontium-90 onto the oceans, this may not be due to different conditions of strontium-90

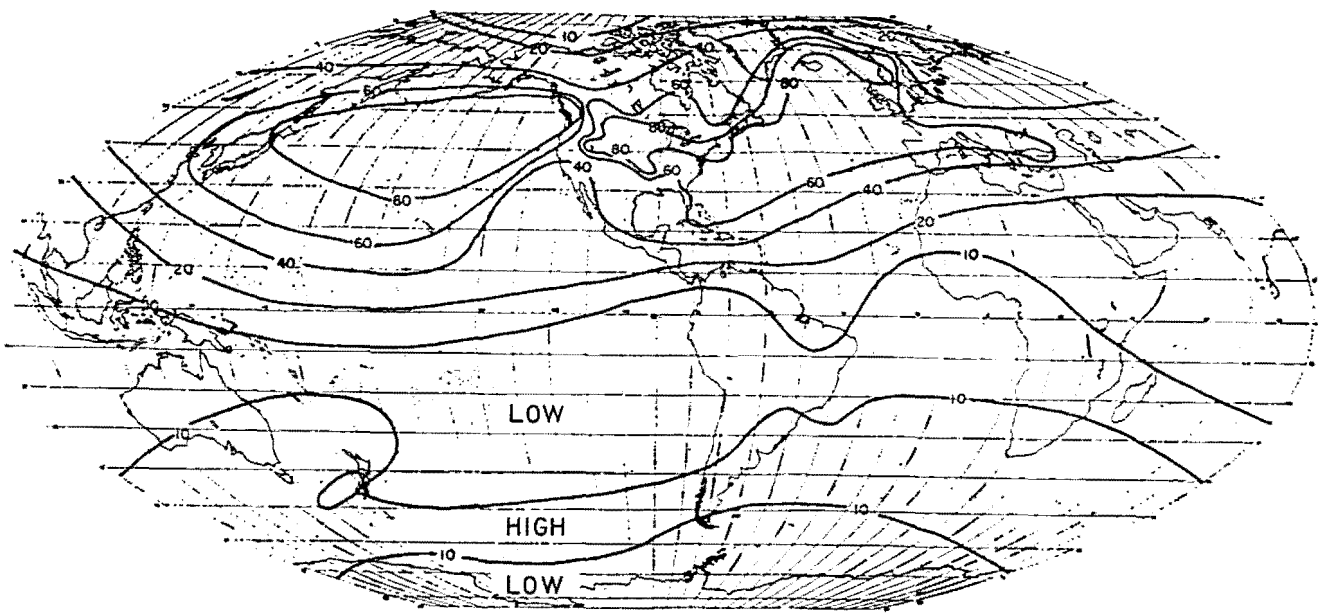


Figure 6. Isolines of cumulative ^{90}Sr deposits based on analyses of soils collected 1965-1967[50] (mCi km^{-2})

removal from the lower troposphere over the oceans from those over land.

25. Karol[57] studied the deposition of radio-active aerosols from the troposphere onto the land and sea surfaces, using a quantitative meteorological model and data on surface-air concentrations. His computations from the model indicate that, within a zonal belt, the average rate of deposition on land and on the sea should be the same.

26. In view of the above considerations, the fall-out over the ocean per unit area in each latitude band is assumed, as in previous reports and for the purposes of the Committee, to be equal to that over the land.

B. Artificial radio-activity in food and tissues

1. *Strontium-90*

27. The levels of strontium-90 in milk and whole diet in the period 1966-1968 are shown in tables III and IV, respectively. In the northern hemisphere, levels have been declining steadily from the peaks of 1963. Based on annual averages, the over-all decline up to 1968 has been by a factor of between three and four. In the southern hemisphere, maximum contamination levels were reached somewhat later, and the subsequent decline has been less marked. Levels are still generally higher in the northern hemisphere than they are in the southern hemisphere, though the difference had narrowed considerably by 1968. In some areas, particularly the Faroe Islands and Iceland, levels of strontium-90 in milk and diet are significantly higher than the average values typical for most of the northern temperate zone. As already indicated in earlier reports, these elevated levels are mainly due to high rainfall and poor soil conditions, particularly low calcium content.

28. The decline in strontium-90 levels reflects the decrease in the annual rate of deposition, which by 1968 was very small, so that levels of strontium-90 in food-stuffs during that year were largely due to absorption from the accumulated deposit in soil. It is to be expected that the further decline in contamination levels will, from now on, be much slower, as they will follow the processes of decay and leaching of strontium-90 in soil.

29. Strontium-90 levels in human bone (table V) are also declining. As expected, the highest rate of decline has been observed in bone from the younger age groups (figure 7), but measurements on adult vertebrae from the northern hemisphere have also indicated declining levels from the peaks experienced in 1965 and 1966. In the case of Denmark, for example, $^{90}Sr/Ca$ ratios in adult vertebrae in 1968 were about 25 per cent lower than the peak levels observed in 1965. Measurements of the levels in other bones, particularly in the slower metabolizing long-bone shafts, are less plentiful, but there is an indication that the 1968 levels may be slightly lower than those in 1967 (figure 7).

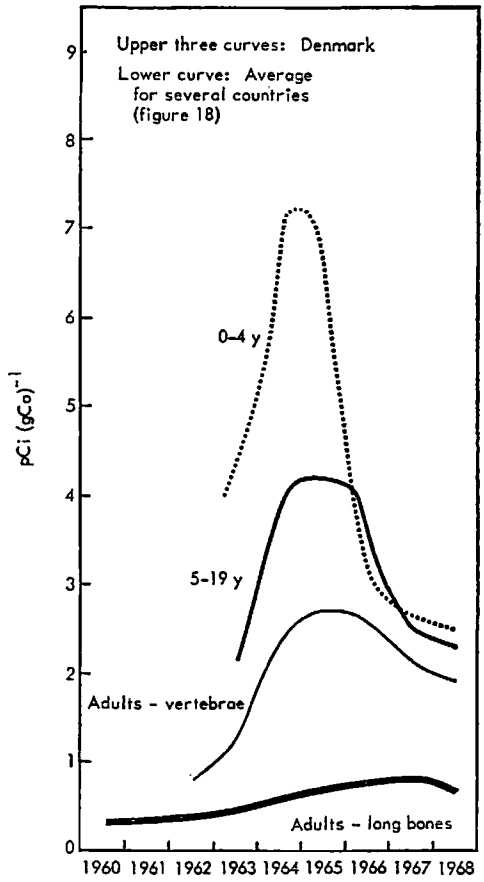


Figure 7. Time variation of $^{90}Sr/Ca$ ratios in human bone for various age groups

2. *Caesium-137*

30. The annual mean levels of caesium-137 in milk declined steadily in the northern hemisphere from 1965 to 1967 (table III). The levels in 1967 were of the order of 10-20 per cent of the 1964 peak values. In the southern hemisphere, the decrease has been smaller. The available 1968 data indicate that the levels in milk in some countries of the northern hemisphere have increased since the middle of the year as a result of deposition from recent nuclear explosions.[57, 58] The observations of the caesium-137 content of whole diets, summarized in table IV, indicate that levels have varied in the same way as they have in milk. In some regions of the world (for example, in some parts of Florida (United States),[59] New Zealand,[23-25] Norway,[61] the Ukrainian Soviet Socialist Republic[60] and and the United Kingdom,[7] and in the Faroe Islands[62] and Jamaica[63]), levels of caesium-137 in milk, and in several areas (for example, Florida[59] and the Ukrainian SSR), levels in meat, are substantially higher than the corresponding latitudinal averages. These higher levels are possibly due, as in the case of strontium-90, to a combination of high rainfall and specific soil conditions.

31. Changes in dietary contamination have been reflected in changes of caesium-137 levels in man (table VI). The mean body burdens in 1967 have usually been about 30 per cent of the 1964 values. The smaller decrease of body burdens compared with that in milk levels, is mainly due to the fact that part of the diet is produced the year before consumption. The exceptionally high body burdens observed in subarctic regions persist, and it seems that the relative rate of decrease is smaller than that in temperature regions as a whole.

3. *Iodine-131*

32. The atmospheric tests carried out in the southern hemisphere during the years 1966-1968 resulted in measurable iodine-131 levels in milk in South America,

Africa and the south Pacific region (table VII). The highest integrated level reported from one explosion series was 27 nCi d l^{-1} in the Buenos Aires area in the second half of 1966.

33. In the northern hemisphere, detectable levels of iodine-131 were observed in Japan after atmospheric explosions in 1966 and 1967[5, 7] and in the United Kingdom in January 1967.[65]

4. *Carbon-14*

34. The concentration of carbon-14 in the human body has been steadily approaching tropospheric levels. Since 1966, the body content has been approximately in equilibrium with the now slowly decreasing tropospheric levels arising from injections before 1963 (figure 8).[66]

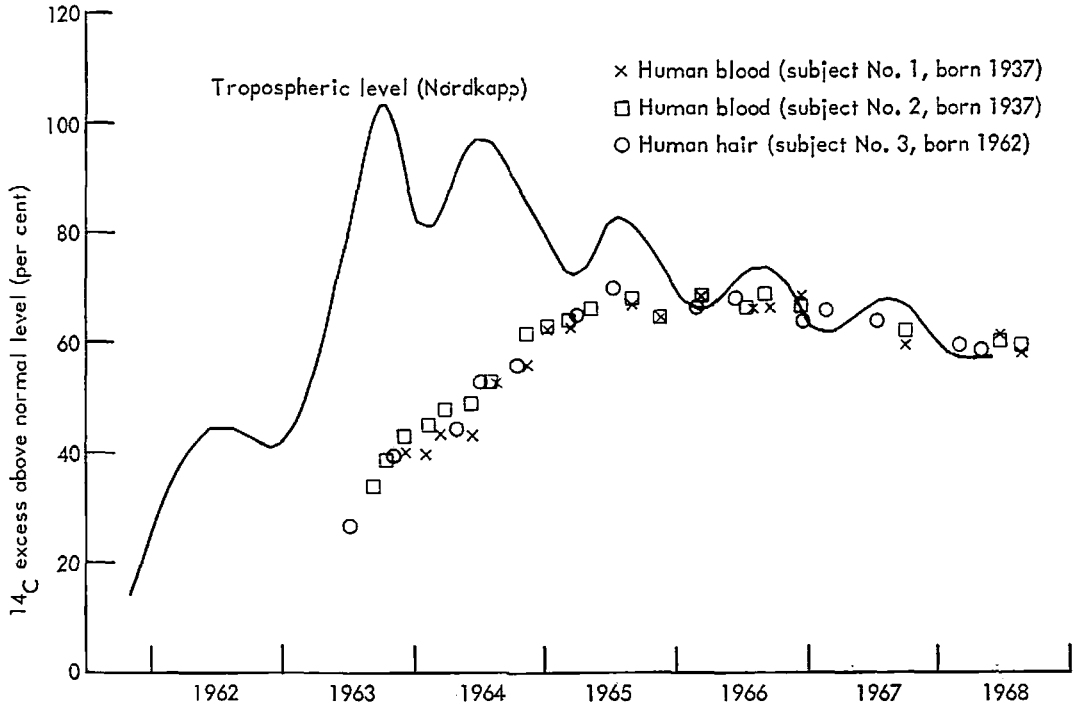


Figure 8. ^{14}C concentration trends in the troposphere and in human blood and hair in Scandinavia[66]

III. Assessment of radiation doses from environmental contamination

A. General

1. *Concept of the dose commitment*

35. When a group of persons is exposed to radiation, it is often desirable to estimate the expected frequency of the injurious effects that may follow. If dose and effect are linearly related and there is no threshold, neither the individual doses nor the time distribution of the dose need be known, and the frequency is obtained from the product of the average radiation dose received and the rate of induction of the biological effect of interest per unit of dose. It is called the absolute risk and represents the probability that the average individual will show the effect after receiving a given dose.

36. However, since the rate of induction of certain effects may vary with dose and dose rate, the actual rates of induction at the levels of radiation to which human populations are exposed cannot necessarily be specified, and thus absolute risks cannot be estimated.

37. For doses of a similar order of magnitude, however, and as long as linearity may be assumed, an approximate comparison of the risks from two sources can be made by considering the ratio of the radiation doses delivered to the same tissue by each source during the same time interval. The dose rate from natural radiation is a convenient reference for this purpose.

38. If, however, a source gives rise to radiation at a varying rate, it is convenient to integrate the mean per capita dose rate over an infinite period of time. As long as the dose thus calculated is finite, some indication of the relative risk can be obtained from the ratio of the dose to that delivered over a finite time interval (for example, one year) by a reference source such as natural background.

39. As a measure of the mean integrated doses, the Committee in its 1962 report[67] adopted the concept of the dose commitment proposed by Lindell.[68]

2. *Definition of the dose commitment*

40. The dose commitment was defined by the Committee in the annexes of the 1964[69] and 1966[70] reports. In the latter, it was defined as follows: "...the dose commitment to a given tissue is...the integral over infinite time of the average dose rates delivered to the world's population as a result of a specific practice, e.g. a given series of nuclear explosions. The actual exposures may occur over many years after the explosions have taken place and may be received by individuals not yet born at the time of the explosions...".

41. When a population is exposed to ionizing radiation, the tissues of individual members receive radiation doses, the magnitudes of which depend on complex

physical and biological factors. If $R_i(t)$ is the dose rate to the tissue under consideration received at time t by an individual i born at time t_i, the dose received up to time t is

$$D_i(t) = \int_{t_i}^{t} R_i(\tau)d\tau, \qquad (1)$$

where $R_i(\tau)$ can assume values other than zero only during the individual's lifetime.

42. If, at time τ, the population consists of $N(\tau)$ individuals, then the average dose rate at that time is, summing over all is,

$$R(\tau) = \frac{1}{N(\tau)}\Sigma R_i(\tau). \qquad (2)$$

and the average dose received up to time t by the population is

$$D_p(t) = \int_{-\infty}^{t} R(\tau)d\tau. \qquad (3)$$

The use of $-\infty$ as the lower integration limit in equation (3) conveniently avoids the need to define the time scale relative to the exposure.

43. The average dose received by the population, accumulated over infinite time, is

$$D_p(\infty) = \int_{-\infty}^{\infty} R(\tau)d\tau. \qquad (4)$$

and is called the dose commitment.

3. *General problems of estimating dose commitments*

44. The age structure of a population is defined by three functions of time:

$N(t)$ = the total number of people in the population at time t;

$\nu(t)$ = the birth-rate at time t;

$f(t,\theta)$ = the probability that a person born at time θ is alive at time t.

For the purposes of the present discussion, these three functions will be regarded formally as being continuous.

45. The size of a cohort born in a small time interval $d\theta$ around time θ is then

$$N(\theta)\nu(\theta)d\theta, \qquad (5)$$

and the size at some later time t will be

$$f(t,\theta)N(\theta)\nu(\theta)d\theta. \qquad (6)$$

46. If the mean dose rate at time τ to the living members of the cohort is $R(\tau,\theta)$, the mean dose accumulated up to time t will be

$$D(t\theta) = \int_{\theta}^{t} R(\tau,\theta)f(\tau,\theta)d\tau. \qquad (7)$$

At time t, each cohort θ contributes a fraction

$$\frac{f(t,\theta)N(\theta)\nu(\theta)\,d\theta}{N(t)} \qquad (8)$$

to the total population, and the mean population dose rate will therefore be

$$R(t) = \int_{-\infty}^{t} \frac{R(t,\theta)f(t,\theta)N(\theta)\nu(\theta)d\theta}{N(t)} \qquad (9)$$

from which the dose commitment as defined in paragraph 43 is obtained.

47. Equation (9) simplifies considerably in the special case of a stationary population in which birth-rate ν and average life span u_m are constant and related by

$$\nu = \frac{1}{u_m} \qquad (10)$$

so that

$$D_p(\infty) = \frac{1}{u_m}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} R(t,\theta)f(t,\theta)d\theta dt = \frac{1}{u_m}E_c(\infty). \qquad (11)$$

where

$$E_c(\infty) = \int_{-\infty}^{\infty} D(\infty,\theta)d\theta \qquad (12)$$

is the mean infinite dose integral over all cohorts. In the case of a single individual, $D_i(\infty) = E_i(\infty)$.

48. The numerical values of $E_c(\infty)/u_m$ and $D_p(\infty)$ in real populations are practically the same for all nuclides of interest in the present connexion, with the exception of strontium-90, where the difference is, at most, 20 per cent. $E_c(\infty)/u_m$ can therefore be used as an approximation for the dose commitment, as this has some advantages. Firstly, its value is easier to estimate than that of the dose commitment itself, and, secondly, the numerical estimates obtained are less sensitive to assumptions concerning the demographic characteristics of the population.

49. The dose commitment to specific tissues may require special treatment. For example, the dose to the gonads is associated with the genetic risk only to the end of the reproductive period. The genetic dose commitment is obtained therefore by replacing the survival function $f(u)$ with a corresponding fertility function $f_g(u)$. If all births are assumed to occur at the mean reproductive age u_g of the parents, then

$$\begin{aligned} f_g(u) &= 1, \quad \text{when } u \leqslant u_g; \\ f_g(u) &= 0, \quad \text{when } u > u_g. \end{aligned} \qquad (13)$$

50. In many cases, there is an appreciable lag between the receipt of a dose and the overt manifestation of biological damage. The effect of this lag ∂ can be roughly taken care of by replacing the mean life span u_m by $u_m - \partial$. In practice, however, the distribution of lag times, particularly at low dose rates, is not well enough known to make it possible to allow for this effect in the calculation, and it is therefore usually neglected.

51. The radiation doses received by fœtuses are not normally included in the dose commitment. Not only is the contribution extremely small, but the type of damage suffered, as well as the relative tissue sensitivities, may not be the same at this stage as they may be later in life. It may be useful therefore to define a separate dose commitment for the fœtal subpopulation. Thus,

$$D_f(\infty) = \int_{-\infty}^{\infty} R_f(\tau)d\tau, \qquad (14)$$

where $R_f(\infty)$ is the mean dose rate delivered to the fœtus during an age interval Δu in which the fœtus is susceptible to a particular type of damage; otherwise, $R_f(\tau) = 0$. The size of the subpopulation is $\nu N \Delta u$. Fœtal rates from external sources and from internal sources that are reasonably uniformly distributed will be about the same as those received by the mother so that, for these sources, $D_f(\infty) \approx D_g(\infty)$. To estimate the dose rates to the foetus from particular radio-nuclides, the distribution of these radio-active sources in the mother and in the foetus must be known.

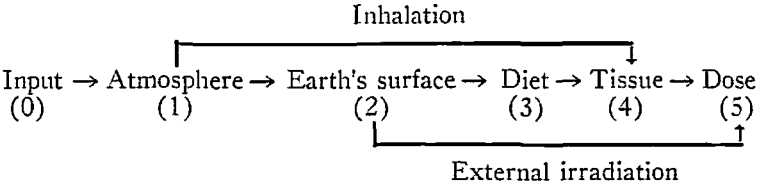
52. Although the dose commitment has mainly been applied to the case of exposure of the world population to radiation from nuclear tests, the concept is, in principle, applicable to other cases. For estimating the value of the dose commitment, however, it may be necessary to take into account various specific properties affecting the distribution of dose among members of the population. The dose commitment is then obtained as the average of the dose commitments to the relevant subpopulations, appropriately weighted by subpopulation size.

B. General transfer functions

1. *Introduction*

53. Doses due to environmental contamination from nuclear tests are delivered to tissues from sources inside and outside the body. In the latter case, the dose commitment can, in principle, be estimated straightforwardly, following the general procedures discussed in the previous section. In the case of doses resulting from radio-nuclides deposited within the body, the calculations are complicated because there is no practical way of measuring tissue doses directly from such sources. The primary measurement therefore is the burden of the nuclide in the body or tissue rather than the dose rate, and the latter must be calculated from physical principles and the distribution of the source within the body.

54. Calculating the dose commitment then becomes mainly a problem of predicting changes in the amounts and distribution in the body of the relevant radio-nuclides. In practice, this may involve not only considerations of the metabolism of the nuclides in various organs and tissues but also in food-stuffs. The chain of events leading from the primary injection of radio-active material into the atmosphere to irradiation of tissues can be represented schematically as follows:



Some of the possible simultaneous pathways are shown in the diagram, indicating the possibility that several steps may be bypassed.

55. Since the dose commitment from a given source is the integral over infinite time of the mean per capita dose rate resulting from that input, steps in the sequence from input to the final dose commitment can be conveniently described in terms of the ratios of the infinite integrals of appropriate quantities in step j of the sequence to the infinite integral of the appropriate quantity in the preceding step i. These ratios define the transfer coefficients P_{ij} that appear as links in the pathway from input of radio-activity into the atmosphere to the subsequent radiation dose to man.

56. The tissue dose from a given source, acting through a given sequence or chain of events, is the product of the input from that source and of all the relevant transfer coefficients. The total dose rate to the tissue is then the sum of the doses contributed by each sequence. For instance,

$$Dose = Input\ [(P_{01}P_{12}P_{23}P_{34}P_{45}) + (P_{01}P_{14}P_{45}) + (P_{01}P_{12}P_{25})] \qquad (15)$$

57. Reference will sometimes be made to the value of the coefficient obtained when numerator and denominator have been integrated to some finite time. In this case, the general symbol t or a specific year will be given in parentheses immediately following the symbol P. In some sequences, intermediate steps may not be involved, and this will be indicated by the numeric suffixes attached to the symbol P. For example, the case of external radiation in which diet and tissue steps are not involved will be referred to as P_{25}. On the other hand, cases will arise in which an intermediate step, although involved, may not in practice be treated separately in the calculations. This will be indicated by the use of a single symbol P with a suffix showing the numbers of all the steps implicitly included. For example, P_{234} indicates the ratio of the infinite-time integral of the levels in tissue to the infinite-time integral of the fall-out deposit.

58. The units in which the values of the P coefficients will be expressed vary with the specific nuclide and with the nature of the quantities being linked.

2. *Specific transfer functions*

(a) *Transfer from primary source to atmosphere (P_{01})*

59. A source of radio-active environmental pollution, such as a nuclear explosion, is characterized by the production rate U of the nuclide considered. Depending on conditions, variable amounts of the radio-active materials are released into the environment. If the rate of release into the atmosphere is W, the transfer coefficient P_{01} is defined by

$$P_{01} = \frac{\int_{-\infty}^{\infty} W dt}{\int_{-\infty}^{\infty} U dt} = \frac{IW}{IU} . \qquad (16)$$

(Subsequently, I will be used as a shorthand notation for integration over time from $-\infty$ to $+\infty$).

60. In the case of nuclear explosions, information on P_{01} is often lacking, and in practice the dose commitment is estimated from IW, i.e., the total amount of radio-active material injected into the atmosphere.

(b) *Transfer from atmosphere to earth's surface (P_{12})*

61. The subsequent atmospheric inventory depends on the rate of removal by deposition onto the earth's surface and on radio-active decay. The transfer coefficient P_{12} is defined by

$$P_{12} = \frac{IF_r}{IW} , \qquad (17)$$

where F_r is the rate of deposition in units of radio-activity per unit time, and IF_r is thus the total integrated deposit.

62. The numerical value of P_{12} depends on the time lag between injection and deposition. If this time lag is small compared to the radio-active half-life of the nuclide considered, P_{12} is close to one. As the mean residence time of debris injected into the stratosphere is, at most, a few years and the residence time in the troposphere is a few weeks, P_{12} for long-lived nuclides, such as strontium-90 and caesium-137, can for practical purposes be taken to be unity. For short-lived nuclides, explosion yield, height of injection, particle-size of the debris, etc. have a considerable influence on the numerical value of P_{12}. For nuclides, such as carbon-14, that appear in gaseous form, no meaningful P_{12} can be defined.

63. The integrated deposit up to time t is defined by

$$F(t) = \int_{-\infty}^{t} F_r(\tau) d\tau \qquad (18)$$

and the cumulative deposit by

$$F_d(t) = \int_{-\infty}^{t} F_r(\tau) e^{-(t-\tau)/T_p} d\tau, \qquad (19)$$

where T_p is the radio-active mean life.

64. Deposition and population density vary widely over the earth's surface, and, for that reason, weighting factors must be applied when relating mean deposition to dose commitment. If $\bar{F}_A$ is the mean deposition in some area A consisting of a number of regions i with deposition F_i and population N_i, a population factor is defined as

$$Z_A = \frac{\Sigma F_i N_i}{\bar{F}_A \Sigma N_i} \qquad (20)$$

which, if the area is the whole globe, can be used to estimate the dose commitment from the mean global deposit. The ratio $G_i = F_i/\bar{F}_A$ is called the geographical factor and can be used to describe local variations in deposit.

(c) *Transfer from deposit to diet (P_{23})*

65. The levels and time distribution of radio-activity in food-stuffs are determined by a number of complex processes occurring in the biosphere. The over-all effect of these processes is summarized by the transfer coefficient P_{23} defined by

$$P_{23} = \frac{IC}{IF_r}, \qquad (21)$$

where C is the mean dietary content of the nuclide considered and IC, consequently, the total integrated dietary content. Often a direct estimate of P_{23} cannot be made, and it is then necessary to consider more closely the processes involved. For this purpose, it is convenient to use a transfer function.

66. If $dC(t,)$ is that part of the radio-active concentration in the diet at time t that is attributable to the amount of radio-activity $F_r(\tau)d\tau$ deposited during the interval $d\tau$ at time τ, the transfer function is defined as

$$K(t,\tau) = \frac{1}{F_r(\tau)} \frac{\partial C(t,\tau)}{\partial \tau}, \qquad (22)$$

where $K(t,\tau)$ is subject only to the assumption that the transfer processes are unaffected by the consequent radiation doses received in the biosphere. The level of activity in the diet at time t, being the sum of the remaining portions of all previous deposits, is therefore

$$C(t) = \int_{-\infty}^{t} K(t,\tau) F_r(\tau) d\tau. \qquad (23)$$

67. Many important processes affecting transfer through the biosphere have a pronounced yearly cycle. The effects of this periodicity can be largely smoothed out by taking yearly averages of $C(t)$ and $F_r(t)$. When $K(t,\tau)$ is derived from such yearly averages, it is generally assumed that the value of $K(t,\tau)$ is determined by the time lapse $t-\tau = u$. The integrated dietary level is then obtained by summing over all times the annual mean amounts in the diet, or

$$IC = \int_{-\infty}^{\infty} C(t) dt = \int_{0}^{\infty} K(u) du \int_{-\infty}^{\infty} F_r(t) dt$$

$$= IF_r \int_{0}^{\infty} K(u) du. \qquad (24)$$

68. If yearly average are used and it is desired to derive an explicit form for the function $K(u)$ from the

levels measured in individual food-stuffs and the annual deposit, the periods selected for averaging should be chosen with care. For example, when a calendar year is selected, it may become necessary to introduce additional terms to allow for the fact that the fodder used in one year may have been produced during a preceding year. Similar problems can also arise in the southern hemisphere because the time of harvest there is spread over two calendar years. Such additional terms are necessary to obtain reliable predictions of future national contamination levels, but, for estimating transfer functions applicable to larger areas from which no measurements are available, results averaged over periods much longer than a year are greatly to be preferred.

69. When deposition occurs in a time period shorter than a year, the consequent level in diet may depend on the time of year when deposition occurs as well as on the elapsed time. In this case,

$$K(t,\tau) \approx K(t_1,t-\tau) \approx K(t_1,u), \qquad (25)$$

where t_1 is the middle of the deposition period. The integrated dietary level is then

$$IC = IF_r \int_0^\infty K(\tau_1,u)du. \qquad (26)$$

70. The transfer coefficient $K(t,\tau)$ has been defined for total diet. In practice, diets are composed of various types of food-stuffs to which different transfer functions may apply. Analogous functions can be derived for each dietary component. If these are denoted by $K_i(u)$, then

$$K(u) = \Sigma\, a_i K_i(u) \qquad (27)$$

and

$$IC = IF_r \Sigma a_i \int_0^\infty K_i(u)du, \qquad (28)$$

where a_i is the fraction that component i contributes to the total diet and the summations are over-all components.

71. The levels of a radio-active nuclide in diet may be expressed in any convenient units, such as activity per unit mass, activity taken in per day or activity per unit mass of some stable element.

72. Very little is known quantitatively about the form of the transfer function $K(u)$, particularly for u longer than a few years, which may be much shorter than the period of interest. In its previous reports, the Committee assumed that

$$K(u) = p_r + p_d\, e^{-\lambda u} \quad 0 < u < 1 \text{ year} \qquad (29)$$

$$= p_d\, e^{-\lambda u} \quad u > 1 \text{ year} \qquad (30)$$

and

$$P_{23} = p_r + p_d\, T_m, \qquad (31)$$

where p_r and p_d are constant factors of proportionality referring to the transfer into food-stuffs from the current deposition and the accumulated deposit in soil, respectively, and where λ is the rate constant of the assumed exponential process by which the nuclide is removed from soil so that T_m is the mean residence time equal to λ^{-1}.

73. The methods available for determining the values of p_r and p_d, as well as the limitations of applying an over-simplified model, were discussed in the Committee's 1962 and subsequent reports. It was shown that, in general, the contributions so far have been largely determined by current deposition. This means that the values of p_d and T_m could not be estimated reliably.

74. Since the Committee's last report, the annual amounts of fall-out have declined sufficiently to make the short-term effects negligible, and estimating a numerical value of P_{23} is now easier. Thus,

$$\int_{-\infty}^{\infty} C(t)dt = \int_{-\infty}^{t'} C(t)dt + \int_{t'}^{\infty} C(t)dt, \qquad (32)$$

and if t' is selected so that $F_r(t') \approx 0$, then, following the Committee's previous assumptions,

$$C(t') = p_d\, F_d(t'), \qquad (33)$$

and the dietary levels at some later time τ are then

$$C(\tau) = p_d\, F_d(t')\, e^{-\lambda(\tau - t')} \qquad (34)$$

so that

$$\int_{t'}^{\infty} C(\tau)d\tau = p_d\, F_d(t')\, \lambda^{-1} \quad = C(t')\, T_m \qquad (35)$$

and

$$IC = \int_{-\infty}^{\infty} C(t)dt = \int_{-\infty}^{t'} C(t)dt + C(t')\, T_m. \qquad (36)$$

The first term on the right is obtained by summing the measured dietary levels up to time t'.[71]

75. The present formulation has the important advantages that (*a*) the estimate of IC thus obtained is less sensitive to errors introduced by the assumptions and becomes increasingly independent of the assumptions as t' increases and (*b*) the integral on the right side of the equation can be considered a lower limit of the estimate of IC, while, if T_m in the second term on the right is taken to be the radio-active mean life, then the sum of the two terms is the maximum value that IC could attain. It is therefore possible to apply limits to the numerical estimate of P_{23} since

$$\int_{-\infty}^{t'} C(t)dt/F(t') < P_{23}$$

$$< \left[\int_{-\infty}^{t'} C(t)dt + C(t')\, T_m \right] /F(t'). \qquad (37)$$

(d) *Transfer from diet to tissue (P_{34})*

76. The transfer coefficient P_{34} is defined by

$$P_{34} = \frac{IQ}{IC}, \tag{38}$$

where Q is the population mean level of radio-activity in a given organ or tissue. The level of radio-activity may be expressed in different ways, such as total amount of radio-activity, activity per unit mass of organ or activity per unit mass of some stable nuclide in the organ.

77. When a given amount of a radio-nuclide enters the body, a varying amount becomes deposited in the different organs and tissues. Subsequently, through both radio-active decay and biological elimination, the levels in the different parts of the body decline. If $dQ(t,\tau)$ is that fraction of the radio-activity in a given organ or tissue at time t following the intake of an amount $C(\tau)d\tau$ during the interval $d\tau$ at time τ, we can define a general transfer function, $m_i(t,\tau)$ as

$$m_i(t,\tau) = \frac{1}{C(\tau)} \frac{\partial Q(t,\tau)}{\partial \tau} . \tag{39}$$

78. The level of activity in the organ or tissue at time t is obtained by summing the contributions from all earlier intakes, that is,

$$Q_i(t) = \int_{-\infty}^{t} C(\tau) m_i(t,\tau) d\tau. \tag{40}$$

Since it can be assumed that, at the low levels of activity in the body resulting from nuclear weapons tests, the various metabolic processes are unaffected by the radiation doses received, equation (40) is generally valid.

79. An average function $m(t,\tau,\theta)$ can similarly be defined for the members of a cohort θ so that

$$Q(t,\theta) = \int_{\theta}^{t} C(\tau) m(t,\tau,\theta) d\tau, \tag{41}$$

where $Q(t,\theta)$ is the mean level of the nuclide at time t in members of the cohort.

80. The mean level weighted by population at time t is, in analogy to the mean population dose rate as defined in equation (9),

$$Q(t) = \int_{-\infty}^{t} \frac{Q(t,\theta) f(t,\theta) N(\theta) \nu(\theta) d\theta}{N(t)} . \tag{42}$$

(e) *Transfer from tissue to dose P_{45}*

81. If an integrated radio-activity level IQ results in a dose commitment $D_p(\infty)$, the transfer coefficient P_{45} is

$$P_{45} = \frac{D_p(\infty)}{IQ} . \tag{43}$$

In this case, the corresponding transfer function is the dose-rate function g.

82. If $Q_i(t)$ is the level of a radio-nuclide in a given organ or tissue of an individual at time t and $R_i(t)$ is the dose rate received by the organ or tissue of interest, the dose-rate function is defined by

$$g_i(t) = \frac{R_i(t)}{Q_i(t)} . \tag{44}$$

The organ or tissue of interest need not necessarily be the same as that containing the nuclide. The dose-rate function is only valid for a given distribution of the nuclide in the body. If different parts of the body have varying metabolic properties resulting in time-dependent changes in the distribution of the nuclide, the dose-rate function will also change with time. An example of this type of behaviour will be discussed later in connexion with strontium-90 in the skeleton.

83. The average dose-rate function for a cohort is similarly defined as

$$g(t,\theta) = \frac{R(t,\theta)}{Q(t,\theta)}, \tag{45}$$

where $Q(t,\theta)$ and $R(t,\theta)$ are, respectively, the level of the nuclide in the organ or tissue of interest and the dose rate at time t averaged over the living members of the cohort θ.

84. In most cases, $g(t,\theta)$ can for practical purposes be regarded as a constant g so that

$$P_{45} = g . \tag{46}$$

When $g(t,\theta)$ varies considerably with age, it is usually more convenient to calculate P_{345} directly.

85. The mean cohort dose rate is, from equation (45), given by

$$R(t,\theta) = Q(t,\theta) g(t,\theta), \tag{47}$$

and thus, according to equation (41),

$$R(t,\theta) = g(t,\theta) \int_{\theta}^{t} C(\tau) m(t,\tau,\theta) d\tau \tag{48}$$

and equation (7)

$$D(t,\theta) = \int_{\theta}^{t} f(t'\theta) g(t',\theta) \left[\int_{\theta}^{t'} C(\tau) m(t',\tau,\theta) d\tau \right] dt' \tag{49}$$

in which it is convenient to change the order of integration to obtain the equivalent expression

$$D(t,\theta) = \int_{\theta}^{t} C(t') \left[\int_{t'}^{t} f(\tau,\theta) g(\tau,\theta) m(\tau,t',\theta) d\tau \right] dt'. \tag{50}$$

86. Adding together the mean doses for all the cohorts in a population gives

$$E_c(t) = \int_{-\infty}^{t} D(t,\theta) d\theta =$$

$$\int_{-\infty}^{t} \int_{\theta}^{t} C(t') \left[\int_{t'}^{t} f(\tau,\theta) g(\tau,\theta) m(\tau,t',\theta) d\tau \right] dt' d\theta. \tag{51}$$

When the fractional survival of the members of a cohort depends only upon age and is therefore inde-

pendent of θ, then $f(\tau,\theta) = f(\tau-\theta) = f(u)$ where u is the age of the cohort at time t. Similarly, when physiological processes and dietary habits are also constant in time and depend only upon the age of the cohort,

$$g(\tau,\theta) = g(\tau - \theta) = g(u) \qquad (52)$$

and

$$m(\tau,t'\theta) = m(\tau - \theta,t' - \theta) = m(u,u'), \qquad (53)$$

where u' is the cohort age at time t'. Equation (51) can then, after integrating to infinity over all cohorts, be written

$$E_c(\infty) = \int_{-\infty}^{\infty} C(t)dt \int_{0}^{\infty}\int_{u'}^{\infty} f(u)g(u)m(u,u')dudu', \qquad (54)$$

in which the double integral is constant in time so that

$$E_c(\infty) = A_1 \int_{-\infty}^{\infty} C(t)dt \qquad (55)$$

with

$$A_1 = \int_{0}^{\infty}\int_{u'}^{\infty} g(u)f(u)m(u,u')dudu'. \qquad (56)$$

87. Thus, in principle, the value of $E_c(\infty)$ can be estimated if the value of the constant A_1 and the accumulated levels of the nuclide in the diet are known and if the physiological and demographic properties of the population considered in deriving equation (54) are generally valid. Combining equations (11) and (55) and bearing in mind the considerations in paragraph 48, it follows that

$$P_{s45} = \frac{D_p(\infty)}{IC} \approx \frac{E_c(\infty)}{u_m IC} = \frac{A_1}{u_m}. \qquad (57)$$

The practical problems of evaluating the constant A_1 and applying equation (57) to real populations vary markedly according to the different radio-nuclides involved and will be left to later sections.

(f) *Dose from external radiation (P_{25})*

88. If a deposit IF_r results in a dose commitment due to external radiation of $D_{pext}(\infty)$, the transfer coefficient P_{25} is

$$P_{25} = \frac{D_{pext}(\infty)}{IF_r}. \qquad (58)$$

89. The corresponding transfer function is defined as

$$h(t,\tau) = \frac{1}{F_r(\tau)} \frac{\partial R(t,\tau)}{\partial \tau} \qquad (59)$$

in analogy with transfer functions discussed earlier. In practice, $h(t,\tau)$ is normally approximated by

$$h(t,\tau) = h_{oi} e^{-\lambda_i(t-\tau)}, \qquad (60)$$

where h_{oi} is a dose-rate conversion factor, accounting for the average effects of weathering, shielding by buildings, etc., on which the properties of $h(t,\tau)$ depend in a complicated manner.

C. Transfer of specific nuclides

1. *Strontium-90*

(a) *Metabolism in man*

90. In previous reports, the time integral of the strontium-90 body burden was estimated from the time integral of the levels of the nuclide in diet using a theoretical model of uptake and elimination of calcium in bone together with a proportionality factor (observed ratio) allowing for the differential transfer of calcium and strontium from diet to bone. By contrast, in the present report, the time integral of the body burden is estimated from the levels of strontium-90 measured in human skeletons. This method depends more critically on knowing how strontium-90 is distributed and retained in the skeleton. The experimental foundation for the values of the parameters to be used in the new method of estimation are reviewed in the following paragraphs. It will be shown later that the estimates of the diet to bone transfer coefficient P_{s4} obtained by the two methods agree well with one another. To make for easier comparison of the relative merits of the two methods, a brief summary of the use and limitations of the concept of the observed ratio and other aspects of the relative transfer of calcium and strontium through food chains are also reviewed in the following sections.

(i) *Distribution of strontium-90 in the body*

91. More than 99 per cent of the calcium, stable strontium and strontium-90 in the body is found in the skeleton.[71] The small amount of experimental information available suggests that stable strontium is distributed uniformly throughout the various bones of the skeleton.[72] Similarly, strontium-90 in the skeletons of children and adolescents appears to be uniformly distributed, although no systematic studies have been carried out on a large scale. In contrast, the distribution of strontium-90 in the adult skeleton is not uniform, the highest $^{90}Sr/Ca$ ratios being found in those bones, such as vertebral bodies and ribs, which are predominantly trabecular, and the lowest in those, such as femoral shafts, that consist predominantly of compact bone.

92. To compare measured $^{90}Sr/Ca$ ratios in adult bones from countries in which different types of bone have been collected, normalization factors are required. The normalization factor for a given bone is the ratio of the $^{90}Sr/Ca$ ratio in that bone to the $^{90}Sr/Ca$ ratio either in another bone, selected as standard, or in the whole skeleton. Several investigators have measured normalization factors, and their results are compared in table VIII and figure 9.

93. The number of samples in some cases is small, intraskeletal relationships have not always been measured on the same individuals and there have been differences in methods of computation used by different workers so that these observations are difficult to interpret.

94. There are wide variations between individuals as shown, for example, by a recent study in Czechoslovakia[73] in which $^{90}Sr/Ca$ ratios in vertebrae and femoral shafts of the same individual were compared. In the fifty-four individuals examined, the correlation between the $^{90}Sr/Ca$ ratios in the two bones was only 0.3, which, though significant at the 95 per cent probability level, does indicate that normalization factors

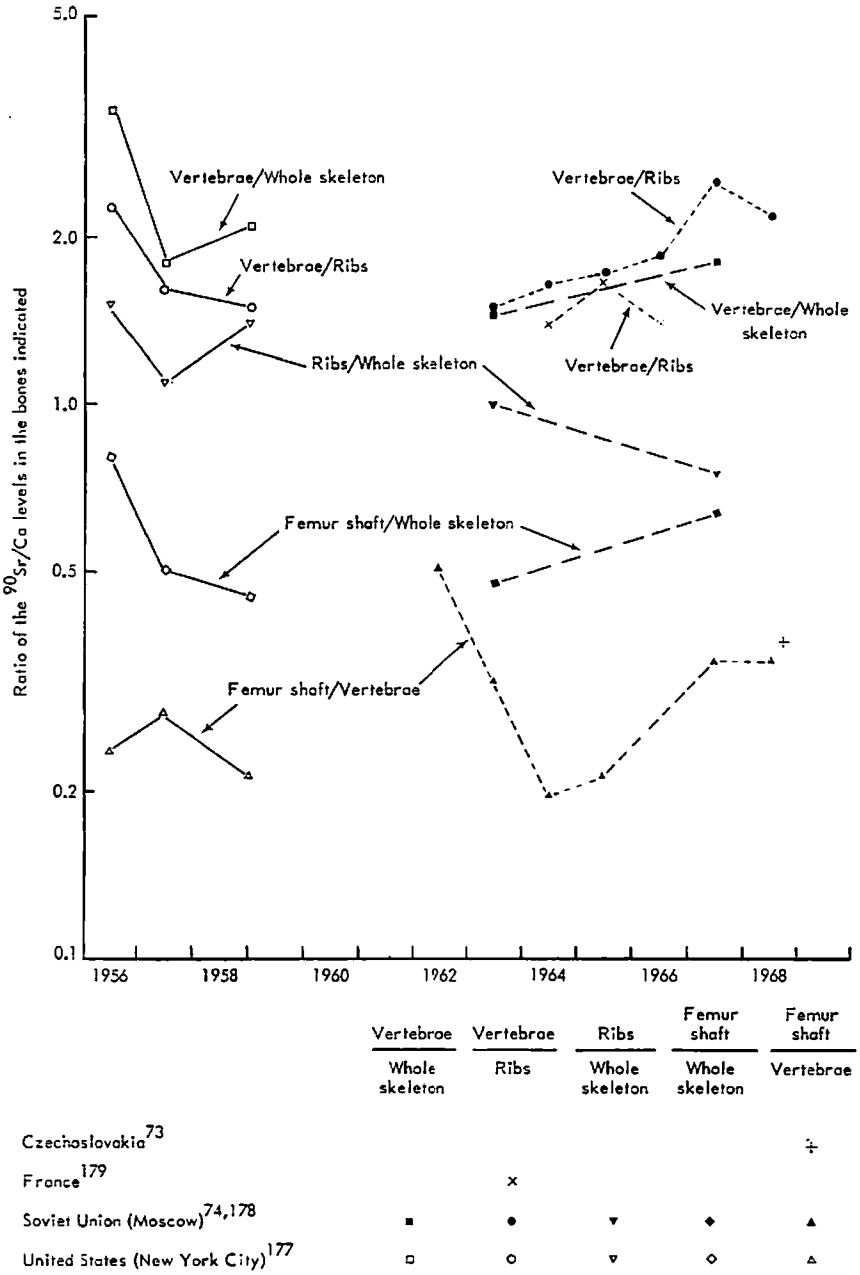


Figure 9. Variability of normalization factors as reported by different workers[a]

[a] Lines connect comparable measurements for ease of reading and are not meant to imply any systematic variation in time.

measured on and applied to a small number of samples may be misleading.

(ii) *Strontium retention functions*

95. *Adults.* Experiments on human subjects in which strontium retention has been measured directly by whole-body counting of strontium-85 or inferred from total excretion, together with measurements made on subjects accidentally contaminated with strontium-90, show that strontium retention can be described by a sum of exponentials such as

$$R(t) = A_1 e^{-\lambda_1 t} + A_2 e^{-\lambda_2 t} + A_3 e^{-\lambda_3 t} . \quad (61)$$

96. The first two time constants correspond to half-lives of two or three days and ten to twenty days, respectively, the third one to a half-life of at least several hundred days. However, the physical half-life of strontium-85 is sixty-five days, and retention can only be followed experimentally for periods up to about 500 days.

97. Longer-term retentions have been followed by Müller *et al.*[75, 76] and by Wenger and Soucas[77] using a group of luminous dial painters accidentally contaminated with strontium-90. Wenger and Soucas found one subject who, just after intake ceased, was excreting strontium-90 with a half-life of about 300 days, while another subject, studied 940 days after intake ceased, showed a half-life of about 2,500 days. Müller studied a group of fifty-two persons for about 2,500 days (just over six years) and found that the excretion curve could be separated into a fraction with a half-life of about 700 days and one with a half-

life of about 6,000 days. Rundo[78] described measurements made on a man with a twenty-year history of exposure to radio-active materials. When his estimated strontium-90 content was plotted semi-logarithmically against time from 1957 to 1967, a good straight line was obtained, corresponding to an effective half-life of 4.2 years and indicating a biological half-life of 5.1 years (1,870 days).

98. Although this spread in the estimates is due in part to individual variation, there are probably also differences in the computational methods used by different investigators as well as differences in the history of contamination between subjects.

99. Alternatively, the results of retention experiments can be fitted to a function of the form

$$R(t) = Ae^{-\lambda t} + Bt^{-C} \qquad (62)$$

where $R(t)$ is the retention t days after intake, B is the fraction of the intake that is retained at one day and released as a power function of time and C is a constant less than unity. So far as the dose commitment is concerned, the exponential term is of no consequence, since λ corresponds to a half-life of a few days only. The power function alone gives a good fit to the strontium-85 retention for periods from twenty or thirty days after the uptake to about 500 days. Müller reports that it still fits after 2,500 days.

100. Since B varies, depending on whether the nuclide is injected directly or is taken by mouth, the power function retention should be represented by

$$R(t) = f'_a Bt^{-C} \qquad (63)$$

where f'_a is the fraction absorbed from the gastro-intestinal tract into the blood. Experimental values for the parameters f'_a, B and C vary from person to person as reported by the same investigator and also between investigators.

101. Several workers[70, 80] have studied small groups of subjects and obtained estimates of B, f'_a and/or the product f'_aB. The considerable variation found among the results of different workers is probably due not only to the small samples studied but also, in cases of ingestion, to differences between experimental conditions. Typical values of the parameters are $f'_a = 0.2$, $B = 0.5$, $C = 0.2$.

102. Measurements of stable strontium in adults[72] suggest that metabolic equilibrium is established, and this is incompatible with a power-law function. Marshall[81] postulated that there is a transition from a power-law to a mono-exponential function occurring t_y years after a single intake and that the time constant of the exponential λ is related to the constant C in the power function by the relation $\lambda = C/t_y$. He estimated that, for humans, t_y is about 3,000 days which, combined with a value of $C = 0.2$, gives $\lambda = 0.025$ y^{-1}.

103. Bryant and Loutit[82] and Rivera and Harley[83] estimated that the fractional replacement rates of stable strontium in adult vertebral bodies and femur shafts are 0.08 y^{-1} and 0.02 y^{-1}. If the body is in strontium balance, these values must be equal to the rates of excretion of the element from these bones, implying that the final mono-exponential function following a single intake has a biological time constant of 0.02 y^{-1} which is in close agreement with Marshall's estimate. During a period of chronic intake of strontium-90, however, the long-term excretion will have components corresponding to the 0.08 y^{-1} elimination rate constant for vertebral-body-like bone and to the 0.02 y^{-1} rate constant for femur-shaft-like bone. However, in a recent study,[84] a model slightly different from that used for estimating the 0.08 y^{-1} and 0.02 y^{-1} replacement rates has been introduced, which yields replacement rates lying between 0.03 and 0.04 y^{-1} for vertebrae and between 0.02 and 0.03 for ribs.

104. If the strontium-90 levels in bone are integrated over decades as is usual when calculating the dose commitment, the contributions from terms having time constants corresponding to half-lives less than a year or so are small and can be neglected. On the other hand, evaluating the long-term excretion rate constant from an analysis of year-to-year variations in the annual mean levels in bone of strontium-90 due to weapons testing is difficult because of the fast initial excretion.

105. *Juveniles.* What has so far been said applies to adults, and it is not known whether and to what extent these considerations apply to children and adolescents (age < 20). Attempts have been made to estimate strontium-90 excretion rates for children from the relatively small amount of data available on levels in bone and in diet.[83, 85, 86] The results obtained are shown in figure 10. In these studies it is implicitly

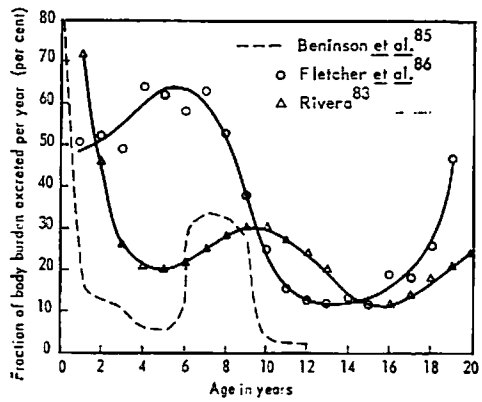


Figure 10. Fraction of body burden excreted per year as a function of age

assumed that annual excretion rates are a function of age only and that, at any given age, strontium-90 is eliminated at the same rate regardless of the time at which the strontium-90 was originally laid down. These assumptions would be strictly correct with a simple exponential excretion function but might be a poor approximation if excretion followed a power law.

(iii) *Observed ratio*

106. The observed ratio between bone and diet is the proportionality factor expressing the relationship at a steady-state between the ^{90}Sr/Ca ratio in bone and the ratio in which the two elements are available from the diet from which the bone is derived. The observed ratio is, within a limited range, independent of the calcium concentration.

107. Interest in the observed ratio rests mainly in the possibility that, through its use, the levels of ^{90}Sr/Ca in bone may be estimated from known levels in diet. The observed ratio can be measured only in systems at a steady-state or where the strontium and

calcium being introduced cannot be confused with that already present. Two methods have been used to estimate the observed ratio for adults:[87] (*a*) measuring the ratio of stable strontium to calcium in the diet and in bone; (*b*) administering simultaneously radio-isotopes of both strontium and calcium. In these methods, it is assumed that the person has consumed a diet with a constant stable strontium to calcium ratio and that the system is at equilibrium.

108. The observed ratio obtained from double-tracer experiments (simultaneous administration of radio-active calcium and strontium isotopes) is not critically dependent upon the interval between intake and measurement, provided sufficient time is allowed for removal of the fractions associated with soft tissues rather than with bone.

109. Values of the observed ratio estimated from stable strontium to calcium ratios in bone and diet for a number of countries are shown in table IX. The range is from 0.15 to 0.33 with an average of 0.22.

110. Values of the observed ratios as a function of age in juveniles have been estimated from strontium-90 to calcium relationships, and the results obtained are shown in figure 11. However these estimates have been derived from the estimates of annual excretion rates referred to in paragraph 105, and therefore the validity of the results thus obtained depends on ex-

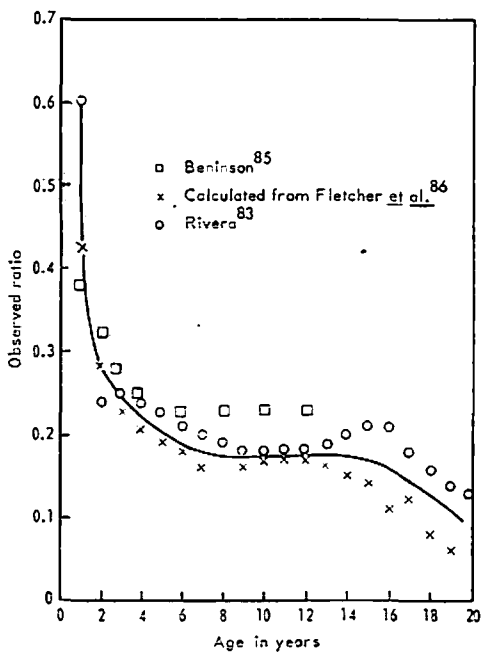


Figure 11. Value of the observed ratio for juveniles

cretion being a mono-exponential rather than a power function of time.

111. *Effect of diet composition on observed ratios.* A number of factors associated with diet composition that may alter the value of the observed ratio have been studied experimentally with laboratory animals.[67] Attempts to demonstrate similar effects in man, however, have generally led to inconclusive results. When measurements are made on levels of strontium-90 from fall-out, the experimental conditions can rarely be defined properly, and the results are difficult to interpret.

112. Knizhnikov and Marei[88] have measured observed ratios for both stable strontium and strontium-90 between bone of still-born and maternal diet in the Soviet Union, finding a value of 0.08 for the former compared with 0.05 for the latter. They suggest that the difference is due to the difference in availability between strontium absorbed from soil and that deposited on the surface of cereal grain. A different interpretation is, however, possible if it is assumed[84] that only a fraction of the strontium and calcium deposited in the fœtus comes from the maternal diet, the rest being derived from the maternal skeleton.

113. Carr *et al.*[89] measured $^{90}Sr/^{85}Sr$ ratios in urine of subjects fed for four weeks on a diet containing whole-grain bread baked from wheat grown on soil contaminated with high levels of strontium-90 and milk from a cow injected with strontium-85 prior to milking. Close agreement between the urinary and dietary isotopic ratios suggests that strontium availability is not affected by the composition of the diet. This experimental result does not conflict with the suggestion of Knizhnikov and Marei, because the strontium-90 in the cereal grain was derived from soil rather than directly deposited.

114. The $^{90}Sr/Ca$ ratios in diets for Moscow and New York City are plotted in figure 12. The average

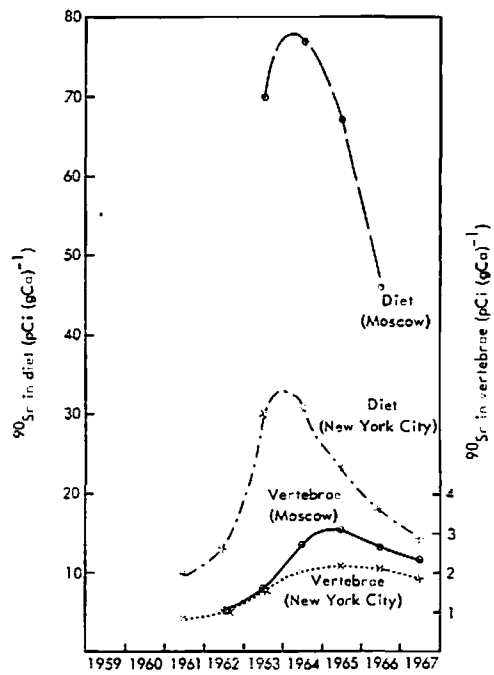


Figure 12. $^{90}Sr/Ca$ ratios in whole diet and adult human vertebrae in Moscow[74, 180] and New York City[181]

diet levels for the two cities during the years 1963-1966 are in the ratio 2.5, but the average levels in adult vertebrae during the same period (also shown in figure 12) are in the ratio of only 1.3, implying that in Moscow the observed ratio for strontium-90 is nearly half that in New York City. On the other hand, the observed ratios for stable strontium are very nearly equal for the two cities (table IX).

115. Knizhnikov and Marei[88] have also suggested that fluorine in drinking water may reduce the value of the observed ratio. Their measurements show stable strontium observed ratios declining from 0.18, when

the fluorine content is low, to half this value when the fluorine concentration is about 1.5 parts per million. Conflicting results have been obtained by other workers,[90] however, and a proper assessment is not yet possible.

(b) *Food-chain mechanisms*

116. Because of the diversity of food-stuffs entering human diets and the many ways in which they are produced, prepared and combined in different areas of the world, a comprehensive quantitative description of the transfer of strontium-90 through food chains would be complex. Further limitations are imposed in practice by the lack of detailed information concerning the calcium intake of a large fraction of the world population, the levels of strontium-90 in the different food-stuffs and the effect of local climatic and agricultural practices on transfer processes.

117. To overcome these problems, the Committee in its 1962 report classified food-stuffs into four broad types—milk, cereals, starchy roots and vegetables—for each of which a representative value of the transfer coefficient was derived from data then available. Likewise, total diets were classified into three main types depending on the proportions contributed to them by the different food-stuff classes. Weighted mean transfer coefficients were thus obtained for each diet-type. When further weighted by the size of the population consuming them and the level of the strontium-90 deposit for the latitude where the food-stuffs were produced, these coefficients could be combined to give a weighted global mean transfer coefficient.

118. In the 1962 and subsequent reports, the global transfer coefficient thus obtained was used to estimate the $^{90}Sr/Ca$ ratio in new bone from the world-wide mean deposit and the observed ratio between bone and diet. The limitations of this approach were discussed in the 1962 report (annex F, paragraphs 12 and 18), and the inherent uncertainties were pointed out.

119. In its 1962 report, the Committee also emphasized that the transfer coefficients would be reliable only when applied over large areas. This conversely implied that transfer coefficients could only be reliably estimated from results averaged over wide areas. For this purpose, means weighted by production or population must be used, as simple arithmetic means of survey results obtained over wide areas where there exist different climatic and agricultural methods may be misleading.

120. In the case of food-stuffs obtained from plants, difficulties arise because of the variability in the reported results of measurements of the calcium as well as of the strontium-90 content, and recent experience has shown that contamination levels expressed in activity per unit mass of calcium are often more variable than when expressed as activity per unit mass of the commodity. A number of factors undoubtedly contribute to the variability, including, particularly, errors of sampling, for the calcium contents of plants vary according to variety, local soil conditions, cultivation methods and local climate.

121. In the tropics and subtropics, soils deficient in calcium are common.[91] Though of low fertility, these soils are used for food production. From such soils, $^{90}Sr/Ca$ ratios in vegetable produce may be significantly higher than would be predicted by empirical relationships established in temperate zones. Nevertheless, this effect is probably offset by the appreciably lower accumulated deposit of strontium-90 in the tropical zone, and, for the purposes of this report, it will be assumed that the integrated diet levels will not exceed those estimated for the populations living in the northern temperate zones where the average strontium-90 deposits are maximal.

(c) *Transfer functions*

(i) *Transfer coefficient—deposit to diet*

122. When the $^{90}Sr/Ca$ ratios in individual food-stuffs are known, values of P_{23} can be estimated by the method described in paragraph 74.

123. *Milk.* The $^{90}Sr/Ca$ ratios in milk from areas or countries in the northern temperate latitudes are shown in table X. There is some scatter among the individual results, reflecting the changing patterns of deposition rates and weather from year to year and from place to place. Nevertheless, over a reasonably long averaging time, the effects of these variations are largely smoothed out.

124. The value of P_{23} (milk) has been calculated from the average annual levels shown in the last column of table X and from the average integrated deposit for the latitudinal band, 65 mCi km^{-2} (figure 13). The average milk level integrated to 1967 is 137 pCi y (gCa)$^{-1}$. Taking the observed level in 1967—9 pCi (gCa)$^{-1}$—and assuming a mean life of strontium-90 in soil of twenty-one years, the integrated level in milk subsequent to 1967 will be 189 pCi y (gCa)$^{-1}$.

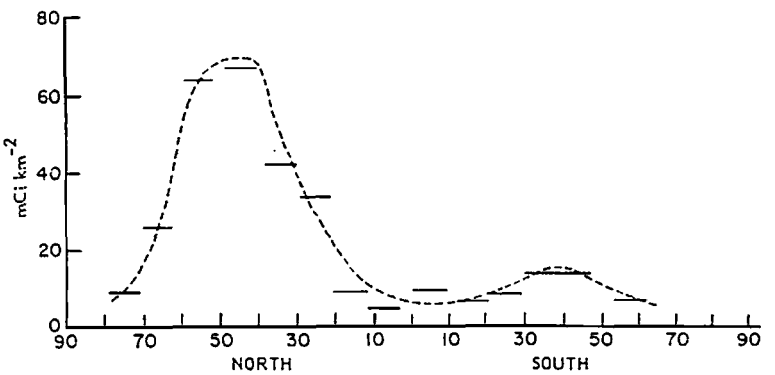


Figure 13. Average latitudinal distribution of deposited ^{90}Sr from analyses of soils collected 1965-1967[50]

Consequently, the integrated level in milk over all time due to tests carried out prior to 1963 will be 137 + 189 = 326 pCi y $(gCa)^{-1}$, corresponding to P_{23} (milk) = 5 pCi y $(gCa)^{-1}$ per mCi km^{-2}.

125. The above calculation is based on data from relatively large but well-defined milk sheds or, in the case of the larger countries, on mean levels weighted either by production or by population. Other cases, where mean levels have not been weighted, have been omitted since the results are not necessarily indicative of the milk consumed by the general population. Also omitted from the calculations are the $^{90}Sr/Ca$ levels in Japanese milk which, because of the use of special cattle feed, are not typical of the latitudinal band as a whole.

126. The countries represented in the calculation contribute about 58 per cent of the total European production and 46 per cent of the total production in the northern hemisphere. If the $^{90}Sr/Ca$ ratios observed in the milk of Moscow and the Ukrainian Soviet Socialist Republic could be taken as representative of milk produced in the Soviet Union, the estimate of P_{23} (milk) would represent about 70 per cent of the total milk production of the northern hemisphere, most of which is produced in the latitudinal band 40-60°N.

127. Similar calculations for the southern hemisphere are not as useful at present because the annual deposition there in 1967 was still significant compared with the accumulated soil deposit. Only about 10 per cent of the world milk production comes from the southern hemisphere, and of this about half is produced in the band of maximum deposition (30-50°S) which includes, principally, Argentina, New Zealand and the more densely populated region of Australia. Cumulative levels (unweighted means) in milk relative to the cumulative deposit in these countries are comparable with the corresponding levels in the middle latitudes of the northern hemisphere, suggesting that the values of P_{23} (milk) in the south are also comparable with those obtained for the north.

128. *Other food-stuffs.* Other food-stuffs, mainly of vegetable origin, include cereals, vegetables and starchy roots. Since starchy roots are of minor importance, they will not be considered further. Rice is the staple food of about half of the world population, and nearly 1,000 million people rely on it for almost all of their caloric requirements. The only systematic study on rice contamination, however, is that reported from Japan[95] where production amounts to about 7 per cent of the world total. Rice is particularly difficult to sample reliably because, being predominantly a subsistence food crop, more than half of the world harvest and as much as three-quarters of the harvest in individual countries never enter markets but are consumed on the farms where the crops are grown.

129. The results obtained in Japan may not be typical of the Far East in general. Most of the rice consumed in the world is of the long-grained *indica* variety, whereas in Japan it is the round or short-grained *japonica* variety that is grown, and Japanese methods of cultivation are unique. The levels of contamination vary widely. In 1961, when deposition rates were low, individual measurements in Japan varied by a factor of two when expressed on a per unit mass basis and by a factor of 4.5 when expressed relative to calcium content. In 1963 and 1964, the range varied by a factor of seven for levels expressed on a per unit mass basis, but no data on calcium contents were given. Rice is milled and polished, and these processes remove some of the minerals and, particularly, much of the strontium-90 content. The Japanese results indicate that 90 per cent may be removed this way.

130. Japan is the only country where the levels of strontium-90 contamination in wheat and rice can be compared. The results show that, on a per unit mass basis, polished rice contains between one-thirtieth and one-fortieth of the amount of strontium-90 of whole-grain wheat, while, on a per gramme of calcium basis, the relative contents vary between one-fifth and one-tenth.

131. The reported strontium-90 contents of whole-grain wheat from countries in the northern temperate zone are shown in figure 14. The levels observed in

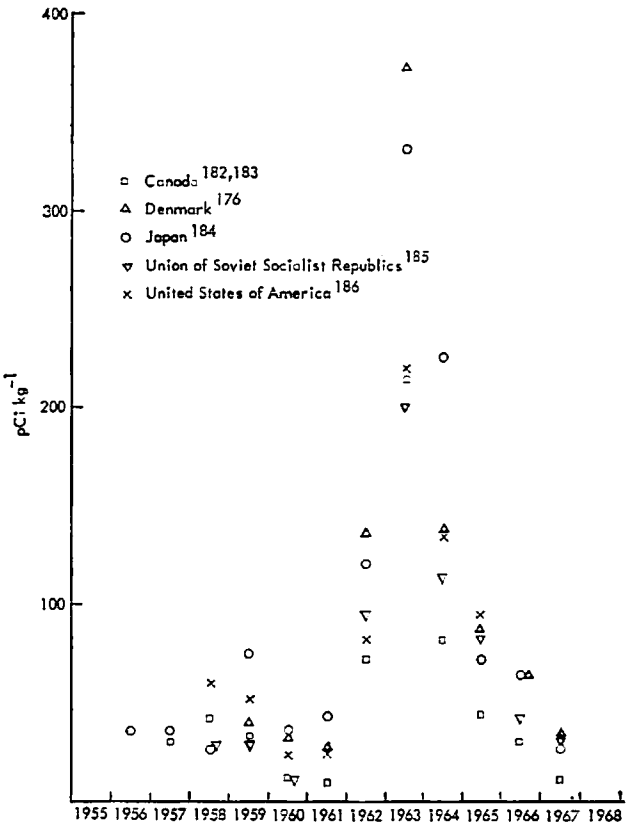


Figure 14. ^{90}Sr content of whole wheat grain in the north temperate zone

North America are generally lower by a factor of two than those of Europe. Few sets of data on levels in wheat and the corresponding deposition cover a sufficient period to allow a meaningful integration. Since using the high levels from Denmark would lead to a conservative estimate of P_{23} (wheat), and since that country has furnished fairly complete results, the estimate of P_{23} (wheat) has been based on these data. If a value of 40 pCi kg^{-1} is taken for each of the years 1955-1958, the cumulative levels up to 1967 are 1,050 pCi y kg^{-1}. The level in 1967 was 34 pCi kg^{-1} which, with a mean life of twenty-one years for strontium-90 in soil, implies future levels integrated to infinite time of about 700 pCi y kg^{-1}. Thus, the total expected contamination in wheat is 1,750 pCi y kg^{-1}, and this, combined with an average deposition of 65 mCi km^{-2} for the latitudinal band, gives a value of P_{23} (wheat)

$= 27$ pCi y kg^{-1} per mCi km^{-2}. An average value of 0.33 gCa kg^{-1} in wheat then gives P_{23} (wheat) $= 81$ pCi y (gCa)$^{-1}$ per mCi km^{-2}.

132. A comprehensive study of contamination in other cereals—rye, oats and barley—is also available from Denmark. The results imply that the value of P_{23} is the same for the four grains when contamination is on a per unit mass basis, whereas for oats it is about half that for wheat, rye and barley when expressed in terms of ^{90}Sr/Ca ratios.

133. While milling removes about 80 per cent of the strontium-90 contamination acquired by direct deposition and about 50 per cent of the calcium, only about two-thirds of the stable strontium are removed by milling,[96-99] implying that the resulting decontamination will be less when most of the strontium-90 comes from soil. Since milling removes two-thirds of the stable strontium, the integrated future level in white flour, assuming 70 per cent extraction, is

$$700\ \frac{1/3}{0.7} = 333 \text{ pCi y kg}^{-1}.$$

Similarly, since milling removes about four-fifths of the strontium-90, the corresponding integrated level up to 1967 is

$$1{,}050\ \frac{1/5}{0.7} = 300 \text{ pCi y kg}^{-1}.$$

Thus, combining the two contributions and dividing by the mean integrated deposition for the north temperate zone (65 mCi km^{-2}) gives a value of P_{23} (white flour) of approximately 10 pCi y kg^{-1} per mCi km^{-2}, corresponding to 50 pCi y (gCa)$^{-1}$ per mCi km^{-2} if the calcium content of white flour is taken to be 0.2 g kg^{-1}. Similar values of P_{23} are implied by results of strontium-90 measurements in Argentina and Australia; the quantitative assessment is, however, difficult because of the relatively high rates of deposition in the southern hemisphere during the year of observations (1967).

134. The levels of strontium-90 contamination of green vegetables have been measured in a few countries in Europe, Australia, Japan and the Soviet Union (figure 15). However, some surveys were discontinued before deposition rates became negligible. Most were started in the early sixties, thus missing some contributions from the earlier years, and all were confined to relatively few types of vegetables. The results from Japan and the Soviet Union are only available on a per unit mass basis. Representative sampling is very difficult because of the large number of varieties grown, the different sizes of crops grown and harvested at various times of the year in different countries and the variable calcium contents of different types of vegetables.

135. Also shown in figure 15 are the levels of strontium-90 in white flour observed in Denmark and the Netherlands. These suggest that, when deposition is high, green vegetables will contain much less strontium-90 per unit mass than white flour, although the reverse appears to be the case when contamination is mainly derived from the soil. It is to be expected therefore that, in the future, levels of contamination per unit mass will be higher in vegetables than in flour. However, differences by a factor of three or four are to be found between individual types of vegetable, and the exact relationship will consequently vary with the composition of the mixture of vegetables. If it is

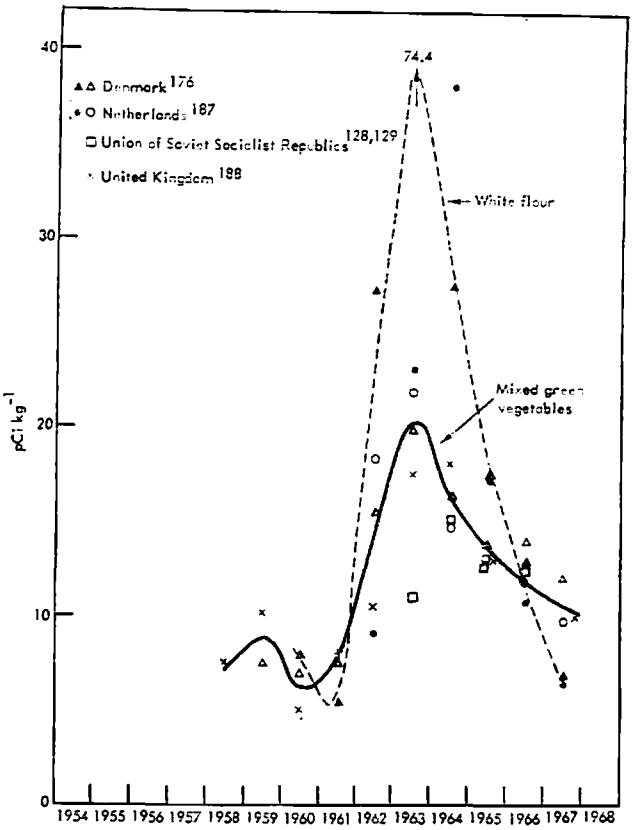


Figure 15. ^{90}Sr content of green vegetables and white flour in the north temperate zone

assumed that contamination levels increased linearly from zero at the beginning of 1954 to the earliest recorded measurements, the data given in figure 15, when treated by the method given in paragraph 74, can be shown to correspond to a value of P_{23} (vegetables) equal to about 5 pCi y kg^{-1} per mCi km^{-2}. The calcium contents of green vegetables are variable, but for present purposes a value of 0.33 gCa kg^{-1} is reasonable so that P_{23} (vegetables) is equal to about 15 pCi y (gCa)$^{-1}$ per mCi km^{-2}.

136. The values mentioned in paragraph 135, however, cannot be used in other areas where types of plants consumed, soils, climate, number of crops and harvest times are different.

137. *Whole diet.* The assumptions underlying the calculations above imply that the relative amounts of strontium-90 in the different types of food observed in 1967 will henceforth remain constant. The ratio of ^{90}Sr/Ca in diet to that in milk in several countries in 1967 varied between one and 1.5 (table XI). With the above-mentioned assumptions, P_{23} (diet) could be estimated to lie between P_{23} (milk) and a value one and a half times higher, namely, between 5 and 7.5 pCi y (gCa)$^{-1}$ per mCi km^{-2}.

138. The transfer coefficient P_{23} for total diet can also be estimated from the P_{23} factors for individual food-stuffs and the corresponding contributions from each food-stuff to the total calcium intake. In a typical high-milk-type diet, these contributions are roughly 80 per cent for milk, 5 per cent for white flour and 15 per cent for vegetables. The value of P_{23} (diet) can therefore be estimated, from equation (28) and the estimates of P_{23} for the three types of food-stuffs, to be

9 pCi y $(gCa)^{-1}$ per mCi km^{-2}, in acceptable agreement with the estimates presented in paragraph 137.

139. Estimates of P_{23} (whole diet) for the high-milk-type diet are insensitive to errors in the estimates of P_{23} for cereals and vegetables. Obviously, for diets in which milk is a less prominent component, the estimates would be more sensitive. Similarly, errors introduced by using the simplifying assumption that strontium-90 is depleted from the soil reservoir by an exponential process having a mean rate constant of 4.5 per cent removal per annum cannot exceed a factor of about two. Thus, in the case of milk, for example, the strontium-90 levels already observed would lead to a value of P_{23} equal to 2.1 pCi y $(gCa)^{-1}$ per mCi km^{-2} (paragraph 124) even if no further uptake of the nuclide from the soil occurred. On the other hand, if radio-active decay (about 2.5 per cent per annum) were the sole removal process, the value of P_{23} could not exceed 8 pCi y $(gCa)^{-1}$ per mCi km^{-2}. The margin of error is even smaller with other food-stuffs because the fraction of the time-integrated levels obtained by extrapolation is smaller.

140. For the purpose of this report, the value of the transfer coefficient P_{23} (whole diet) for the high-milk-type diet is taken to be 9 pCi y $(gCa)^{-1}$ per mCi km^{-2}.

(ii) *Transfer coefficient—diet to tissue*

141. To estimate the transfer coefficient P_{34}, Lindell[68] introduced five basic assumptions:

(*a*) strontium is incorporated into bone at a rate directly proportional to the rate of calcium incorporation;

(*b*) the $^{90}Sr/Ca$ ratio in new bone is proportional to the $^{90}Sr/Ca$ ratio in the diet from which it is derived. The proportionality factor is independent of age and, for the purposes of calculation, is taken to be equal to the observed ratio (OR) in adults under steady-state conditions;

(*c*) strontium-90 is eliminated exponentially with a time constant independent of age;

(*d*) all members of the population have the same mean life span u_m so that

$$f(u) = 1 \qquad 0 < u < u_m$$
$$f(u) = 0 \qquad u \geqslant u_m;$$

(*e*) the dose-rate function γ is constant.

142. If strontium-90 levels in diet and bone are expressed in $^{90}Sr/Ca$ ratios, it follows from the first three assumptions that

$$m(u,u') = OR\,\frac{a(u')}{B(u)}\,e^{-k_1(u-u')}, \qquad (64)$$

where u' is the age at time of uptake; u the age at some later time; $B(u)$ the mass of calcium in the skeleton at age u; $k_1 = k_{sr} + \lambda$ the rate of strontium-90 loss; and a the rate of calcium incorporation given by

$$a(u') = k_0 B_a \qquad u' > 20$$
$$a(u') = \phi(u')(1 + k_0 u') \qquad 0 < u' \leqslant 20$$

in which k_0 is a constant, $\phi(u')$ is a growth function and B_a is the mass of calcium in the adult skeleton. The constant A_1, defined by equation (56) as

$$A_1 = \int_0^\infty \int_{u'}^\infty f(u)g(u)m(u,u')\,du\,du',$$

can then, after introducing assumptions (*d*) and (*e*), be written

$$A_1 = \int_0^{u_m} \int_{u'}^{u_m} m(u,u')\,du\,du' = \gamma \int_0^{u_m} F_m(u')\,du', \qquad (65)$$

where

$$F_m(u') = \int_{u'}^{u_m} m(u,u')\,du, \qquad (66)$$

and is called the dose-increment factor.

143. Lindell defined an average dose-increment factor as

$$\bar{F}_m = \frac{1}{u_m}\int_0^{u_m} F_m(u')\,du' \qquad (67)$$

so that

$$\bar{F}_m = \frac{A_1}{\gamma u_m OR} \qquad (68)$$

Since, according to equation (57), $P_{34}P_{45} = A_1/u_m$ and since $\gamma = P_{45}$, then $P_{34} = \bar{F}_m\,OR$. In its previous reports, the Committee adopted values of 0.6 and 0.25 for $\bar{F}_m$ and OR, respectively, corresponding to $P_{34} = 0.15$. Lindell[68] showed that $\bar{F}_m$ is not critically sensitive to the value of the mean life span nor to the numerical values assigned to k_0 and k_{sr} as long as they are about the same order of magnitude.

144. Alternatively, if measurements of $^{90}Sr/Ca$ ratios in human bone are available for all age groups in the population, P_{34} can be estimated directly, and Lindell's first two assumptions can be avoided. The strontium-90 level integrated up to some time t is

$$G_t = \frac{1}{u_m}\int_{-\infty}^{t} \int_0^{u_m} S(t',u)\,du\,dt'. \qquad (69)$$

The strontium-90 in the bone at time t will further contribute to the exposure so that, if it is assumed that the nuclide is eliminated exponentially, the integrated future levels due to the amounts ingested up to time t will be

$$H_t = \frac{1}{u_m}\int_0^{u_m} \int_{u''}^{u_m} S(t,u'')\,\frac{B(u'')}{B(u)}\,e^{-k_1(u-u'')}\,du\,du'', \qquad (70)$$

where u'' is the age at time t and u is the age at some later time.

145. It follows then that the integrated strontium-90 level in bone due to the amounts ingested through diet up to time t is $G_t + H_t$. Hence,

$$P_{34} = \frac{G_t + H_t}{C_t}, \qquad (71)$$

where

$$C_t = \int_{-\infty}^{t} C(t')dt'. \qquad (72)$$

Equation (70) can be written

$$H_t = \frac{1}{u_m} \int_{0}^{u_m} S(t,u'')W(u'')du'', \qquad (73)$$

where

$$W(u'') = \int_{u''}^{u_m} \frac{B(u'')}{B(u)}\, e^{-k_1(u-u'')}\, du \qquad (74)$$

and is called the integral weighting factor. It has been evaluated for several values of k_1 in adults combined with various excretion functions in children. The results are shown in figure 16.

146. The integral weighting factors are strontium-90 bone burdens integrated over the balance of life for an initial strontium-90 burden of 1 pCi $(gCa)^{-1}$ at age u''. The value of H_t can therefore be obtained for any year by multiplying the appropriate integral weighting factors by the corresponding $^{90}Sr/Ca$ ratios observed in bone in each age group, summing the products over the whole population and dividing the sum by u_m as in equation (73).

147. In practice, the number of samples of bone available in each yearly age group is too small, and therefore average integral weighting factors are calculated for groups of ages. Thus, all samples from persons twenty years of age and over are combined to obtain a single average value for adults, and samples from children and adolescents in the age range five to nineteen years are similarly combined. For ages between zero and four years, it is preferable to have results of bone analyses for each individual year of age, and these are available from a number of countries.

148. Values of H_t have been estimated for adult vertebrae assuming $k_{sr} = 0.1\ y^{-1}$ for this type of bone. The reasons for choosing vertebrae rather than whole skeleton are discussed in paragraph 159. The same value of k_{sr} was assumed for children. Although there is no experimental evidence to support this assumption, the value of H_t obtained does not depend critically on it, both because the effect of calcium accretion during growth is large and because the integrated levels up to twenty years of age contribute less than 25 per cent to the integrated levels of the whole population.

149. The values of P_{34} for each of the years in which data are available have been calculated for Australian vertebrae and are tabulated, together with the values of G_t, H_t and C_t, in table XII. From this it can be seen that, except for the first year or two, P_{34} is, as expected, reasonably constant, the mean value from 1961 to 1967 being 0.21. Apart from possible

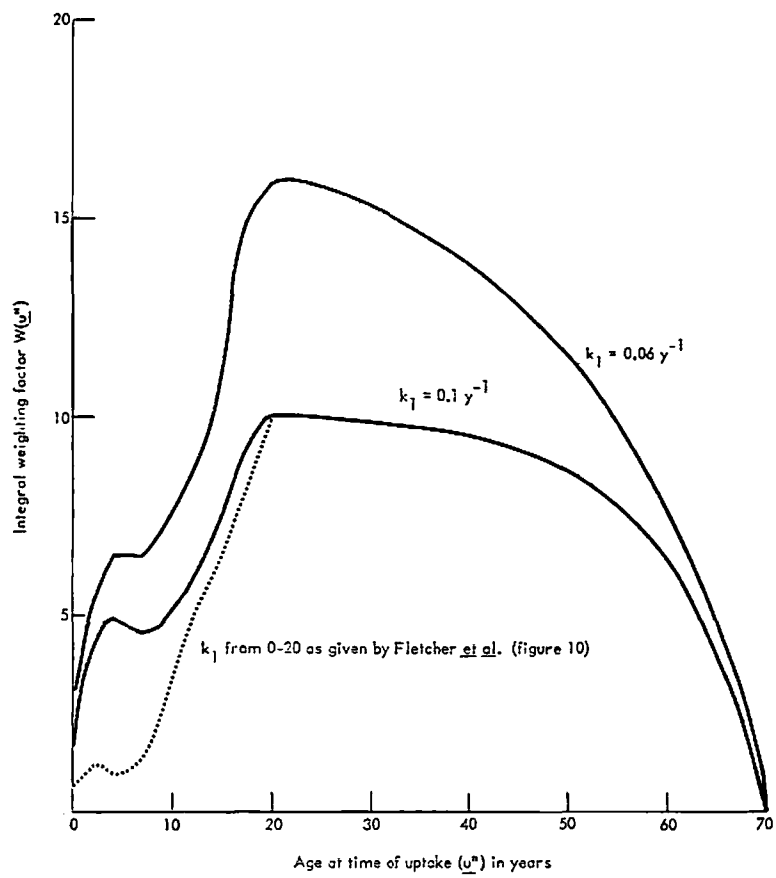


Figure 16. Variation of integral weighting factor $W(u'')$ in bone with age of uptake u'' and ^{90}Sr excretion rate constant

errors (mostly due to sampling) in the original data, the greatest source of uncertainty is the value of the excretion rate for strontium-90. In the absence of further large-scale tests, it will soon become evident whether the value of 0.1 y^{-1} is reasonable or not, for, if the true value is greater or less than this, then the values of P_{34} obtained in future years will either decrease or increase systematically.

150. A value of P_{34} was also calculated for those countries in the north temperate latitudes in which milk contributes a large fraction of the total dietary intake of calcium. For this purpose, the reported $^{90}Sr/Ca$ ratios for each age group were averaged over all the countries from which sufficient data were available (figure 17), and the integrated diet levels were obtained from the average levels in milk of the countries in the same geographical area (table X) multiplied by the average diet-to-milk ratio for this diet type (table XI). The results are shown in table XIII.

151. The mean value of P_{34} equal to 0.2 thus obtained agrees with that previously calculated from the Australian data. The $^{90}Sr/Ca$ ratios measured in vertebrae from Poland and the Soviet Union, also shown in figure 17, lie within the limits of variability of those from countries in which milk is a relatively more important dietary constituent. Despite differences in the levels of dietary contamination in these two countries, the corresponding levels of strontium-90 in bone weighted by population and integrated to 1967 are also about the same, though the corresponding value

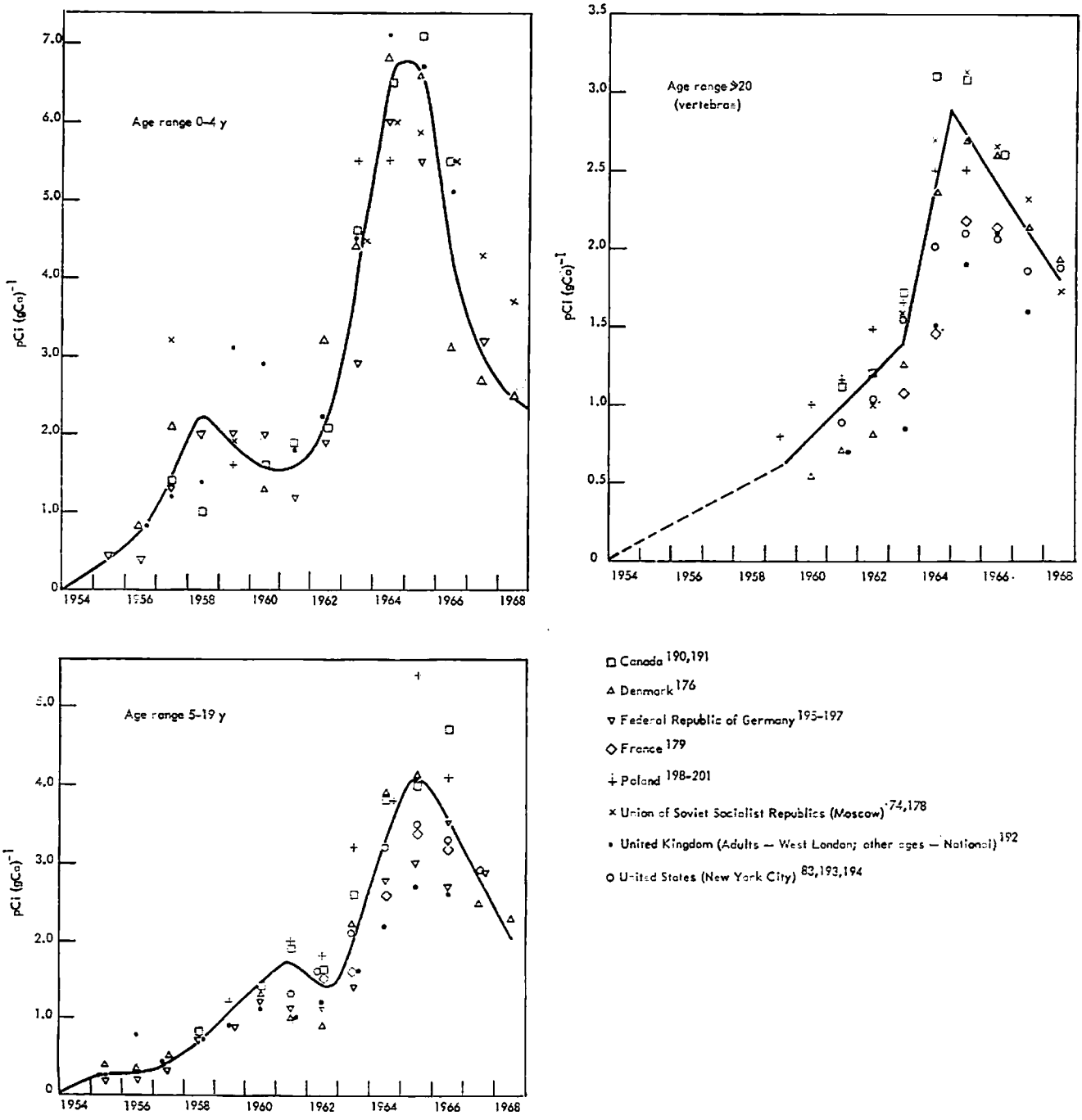


Figure 17. $^{90}Sr/Ca$ ratios in human bone samples in the north temperate zone

of P_{s4} would be about a factor of three lower. The relative strontium-90 levels in adult skeletons for countries in which bones other than vertebrae have been sampled can be estimated from the data in figures 18 and 19. Thus, levels in tibia from Finland are very

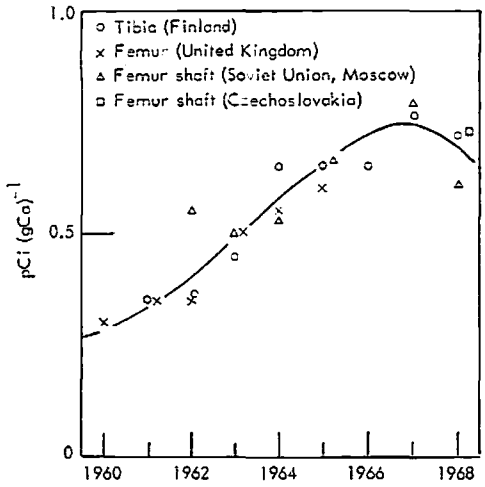


Figure 18. $^{90}Sr/Ca$ ratios in long bones

similar to those measured in femur from the United Kingdom and the Soviet Union (figure 18). On the other hand, when levels of strontium-90 in ribs from

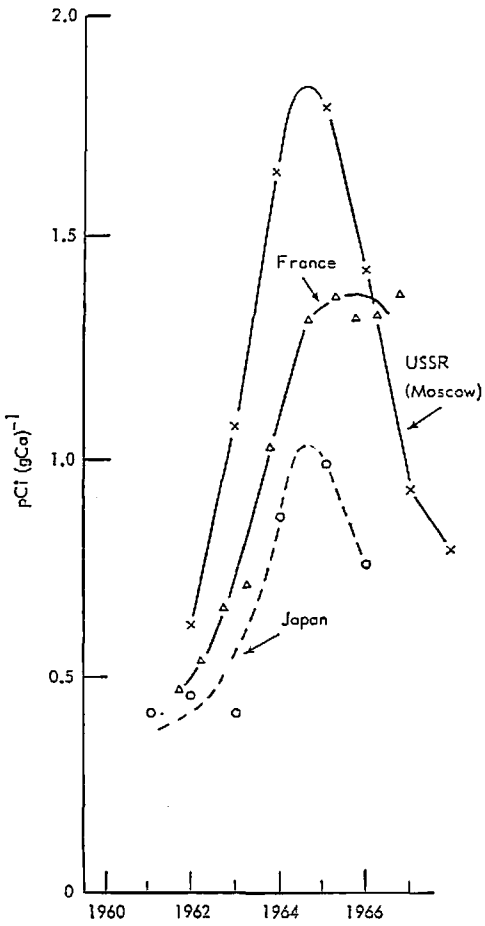


Figure 19. $^{90}Sr/Ca$ ratios in adult ribs

Japan are compared with those from France and the Soviet Union (figure 19), it can be inferred that strontium-90 levels in skeletons from Japan tend to be somewhat lower than the average for the latitudinal band as a whole.

(iii) *Dose-rate factor*

152. *Adults.* The mean dose rates to active bone marrow and endosteal tissue applicable in the case of uniform contamination of the skeleton with strontium-90 have been calculated by Spiers.[317] However, in what has so far been experienced, skeletal contamination in adults has been manifestly non-uniform, $^{90}Sr/Ca$ ratios in typical trabecular bone (vertebral bodies) being more than three times higher than those found in typical compact bone (femur diaphyses). Since the dose rates to bone marrow and endosteal cells are largely due to the strontium-90 contained in trabecular bone, averaging the strontium-90 body burden throughout the whole skeleton underestimates the $^{90}Sr/Ca$ ratio and, hence, the dose.

153. The magnitude of the error introduced when the skeleton is non-uniformly labelled can readily be ascertained by separating the dose contributions from strontium-90 in trabecular and cortical bone and then weighting according to the $^{90}Sr/Ca$ ratios in the two bone types.

154. The results of the calculations are given in tables XIV and XV for bone marrow and endosteal tissues, respectively. From table XIV it is seen that the bone-marrow dose rates arise from two separate sources, that is, from the strontium-90 in the two bone types, trabecular and compact, as follows:

0.369 mrad y^{-1} per pCi $(gCa)^{-1}$ in trabecular bone
0.180 mrad y^{-1} per pCi $(gCa)^{-1}$ in compact bone.

Similarly, from table XV it is seen that the dose rates to endosteal cells are

0.678 mrad y^{-1} per pCi $(gCa)^{-1}$ in trabecular bone
0.206 mrad y^{-1} per pCi $(gCa)^{-1}$ in compact bone.

If the skeleton is uniformly labelled at 1 pCi $(gCa)^{-1}$, then the bone-marrow and endosteal-cell dose rates are, respectively, 0.369+0.180 or 0.55 mrad y^{-1} per pCi $(gCa)^{-1}$, and 0.678+0.206 or 0.88 mrad y^{-1} per pCi $(gCa)^{-1}$. To the latter figure Spiers added a contribution (0.25 mrad y^{-1} per pCi $(gCa)^{-1}$) due to the dose delivered to the endosteal tissues in shafts of long bones. Since this correction was not based on direct experimental data, it must be regarded as an arbitrary safety factor leading to an over-estimate of the dose-rate factor.

155. For the non-uniformly labelled skeleton, it is assumed that the $^{90}Sr/Ca$ ratio found in vertebral bodies is representative of the levels in trabecular bone throughout the skeleton, whereas that in femoral diaphyses is representative of compact bone. From the empirically observed normalization factors in 1967 (table VIII), the levels in vertebral bodies and femoral diaphyses are, to one significant figure, 2 and 0.6 pCi $(gCa)^{-1}$, respectively, when the average $^{90}Sr/Ca$ ratio in whole skeleton is 1 pCi $(gCa)^{-1}$.

156. The weighted mean dose-rate constant to the whole active bone marrow, when the average $^{90}Sr/Ca$ ratio in whole skeleton is 1 pCi $(gCa)^{-1}$, is then calculated as follows:

Trabecular bone contribution=2.0 $0.369 = 0.74$ mrad y^{-1}

Compact bone contribution=0.6 $0.180 = 0.11$ mrad y^{-1}

Total= 0.85 mrad y^{-1}

so that, with a concentration of 1 pCi $(gCa)^{-1}$ in vertebral bodies, the dose rate to the whole active marrow is 0.43 mrad y^{-1}.

157. Similar arguments apply to the dose to the whole endosteal tissue (except the long-bone-shaft endosteum), the weighted mean tissue dose rate to which is calculated as follows:

Trabecular bone contribution=2.0 $0.678 = 1.36$ mrad y^{-1}

Compact bone contribution=0.6 $0.206 = 0.12$ mrad y^{-1}

Total= 1.48 mrad y^{-1}

so that, with a concentration of 1 pCi $(gCa)^{-1}$ in vertebral bodies, the dose rate to endosteal cells is 0.74 mrad y^{-1}. If the long-bone-shaft endosteum contribution is added, the mean dose-rate factor can be shown to be 163 mrad y^{-1} per pCi $(gCa)^{-1}$ averaged over the whole skeleton, or 0.82 mrad y^{-1} per pCi $(gCa)^{-1}$ in vertebral bodies.

158. The dose rates for the whole of the skeleton and the whole of the bone marrow are then

	Bone marrow	*Endosteal tissue*
(a) *Non-uniform*	0.43 mrad y^{-1} per pCi $(gCa)^{-1}$ in vertebral bodies	0.82 mrad y^{-1} per pCi $(gCa)^{-1}$ in vertebral bodies
(b) *Uniform*[a]	0.55 mrad y^{-1} per pCi $(gCa)^{-1}$ in any bone	1.13 mrad y^{-1} per pCi $(gCa)^{-1}$ in any bone,

[a] The dose-rate factors for uniform distribution of strontium-90 given here are the same as given in *Table 6* of publication 11 of the International Commission on Radiological Protection.

where the non-uniform factors apply during at least some part of the lives of those in the population who were adults or late teenagers during the periods of maximum fall-out levels and where the uniform factors apply to those who were children or yet unborn at that time. For present purposes, however, the dose-rate factors for uniform distribution can be applied without serious error throughout the period for which the dose commitment is calculated.

159. There are, however, several advantages to using strontium-90 levels in vertebral bodies for calculating the dose commitment. Vertebral bodies are a convenient source of autoptic bone material and have been widely used in a number of countries. As discussed earlier, there is uncertainty about the values of normalization factors and, particularly, about their future time course. Applying dose-rate factors for vertebral bodies makes it possible to use most of the data directly without multiplying the results by factors that tend to be arbitrary, that may vary with time and that require further assumptions. According to data given by Spiers, vertebral bodies contain more than 40 per cent of the active bone marrow in adults and nearly the same fraction of endosteal cells. Thus, vertebral bodies contain a larger fraction of the critical tissues than any other group of bones, although the largest fractional dose-rate contribution comes from the flat bones—pelvis, clavicles and scapulae—which, however, have not been used in bone surveys. The dose-rate contribution of vertebrae is only slightly less, and these two types of bone together contribute 60 per cent of the total dose rates to bone marrow and endosteum.

160. Strontium-90 is assumed to be uniformly distributed in the skeletons of children and adolescents so that, in the past, normalization factors have been applied only to measurements obtained from bones of persons more than twenty years of age. This has meant that average $^{90}Sr/Ca$ ratios for whole skeletons have shown a sharp discontinuity at age twenty which is not plausible on physiological grounds. The use of $^{90}Sr/Ca$ ratios in adult vertebral bodies largely removes the discontinuity in a rational way.

161. *Children.* Spiers has applied methods similar to those used for adults to calculate dose-rate factors for children. However, the experimental material available to him was very much smaller, consisting only of a vertebra and a femur from a five-year-old child.

162. The dose-rate factor calculated by Spiers for bone marrow in a five-year-old child is 0.82 mrad y^{-1} per pCi $(gCa)^{-1}$, or about 1.5 times the corresponding value for adults with uniformly labelled skeleton. It is not known how this value changes for other ages between birth and twenty years of age. No corresponding estimate of the dose-rate factor for endosteal cells in children is given. However, when estimating the dose commitment of the whole population, the value of the dose-rate functions for adults can, with little error, be taken to be constant with age.

2. *Caesium-137*

163. The dose commitment from ingested caesium-137 is easier to estimate than is that from strontium-90, because caesium-137 can, for dosimetric purposes, be considered to be distributed uniformly in the body and because it is excreted rapidly. In contrast to strontium-90, the long-term uptake of caesium-137 into diet from soil in temperate regions is generally less important than direct deposition on vegetation. The total dietary intake of caesium-137 can be estimated more reliably therefore from directly measured levels, since only a relatively small allowance for long-term uptake is necessary.

164. Caesium-137 and strontium-90 produced by nuclear explosions in the atmosphere are transported to the earth's surface without fractionation, as shown by the relative uniformity of the observed $^{137}Cs/^{90}Sr$ ratios in air and deposit.[12, 13, 34-36, 101]

(a) *Caesium-137 in food chains*

165. The main dietary sources of caesium-137 are milk, meat, vegetables and cereals.[64] In some regions, fish from inland lakes is locally important.[102, 316] In general, however, levels tend to be highest in meat and cereals and lowest in vegetables.[103] Direct comparison of intakes between different regions thus requires observations on representative diets (table IV).

166. Within areas with reasonably uniform deposition and with similar soil types, levels in different food-stuffs are fairly closely correlated.[60, 104] Measurements on a single item can therefore be used to detect regions where large deviations from normal may occur. Milk is convenient for this purpose, as representative samples can be obtained easily and analysis

is simple. A large number of milk analyses from different regions have been reported (table III).

167. When allowance is made for differences in deposition, levels of caesium-137 in diet and milk as a rule vary by relatively small amounts between those regions from which data have been available. Observations from regions with non-western diets are, however, scarce, and no definite conclusions can be drawn about average levels in these areas.

168. Exceptionally high values have been observed in reindeer and caribou meat in subarctic regions. The special conditions in these regions are discussed separately in paragraphs 191 and 192. High milk concentrations have also been observed in other areas (paragraph 30) where the higher uptake seems mainly to be due to predominance of soils low in micaceous clay and exchangeable potassium so that pastures are poor and/or high in organic matter. In addition, high precipitation may in some cases (for example, in mountainous areas) result in enhanced caesium-137 deposition and uptake. Tracer experiments indicate that uptake of caesium-137 from red, lateritic and alluvial soils common in the tropics and subtropics is considerably higher than uptake from the clay soils of temperate regions, but no measurements in local food products or people in the tropics are available.[64, 105]

(b) *Transfer from deposit to diet*

169. The transfer of caesium-137 to diet is normally characterized by high uptake during the first years after deposition and by a relatively small uptake subsequently.[64] No quantitative description of the transfer from deposit to whole diet has so far been attempted. However, in its 1964 report, the Committee accepted that the transfer to milk could be described by the following equation originally applied to British data by Bartlett and Mercer:[106]

$$C(t) = p'_r F_r(t) + p'_{2c} [F_r(t-1) + F_r(t-2)], \quad (75)$$

where $C(t)$ denotes the caesium-137 concentration in milk, $F_r(t)$ the mean deposition rate in year t, and p'_r and p'_{2c} are constants determined empirically from observed levels. Equation (75) gives a transfer coefficient $P_{2s}=p'_r+2p'_{2c}$ and corresponds to a transfer function (paragraph 66) with $K(0) = p'_r$, $K(1) = K(2) = p'_{2c}$ and $K(u) > 2 = 0$. The uptake after more than two years is thus formally neglected.

170. More elaborate models have been used to describe the relationship between levels in deposition and in milk by Bartlett and Russell[107, 108] and by others.[104] In these models, the long-term component has explicitly been taken into account by assuming $K(u) \geqslant 2 = p_a e^{-u/T_m}$, where p_a is a constant derived from tracer experiments.

171. Milk levels show a pronounced yearly cycle depending on deposition rates and agricultural practice, but the yearly mean level is representative of the dietary intake in that year. Meat and grain products, which provide about half of the caesium-137 intake in western-type diet, are often stored and may thus be representative of an earlier fall-out situation. The relative contributions of different types of food-stuffs consumed therefore vary with deposition rates, even though at production level they remain unchanged in any given year. If the dietary levels are integrated over a number of years, the effect of such variations cancel out, but there may remain a long-term change in the proportions by which different types of food contribute to diet, if there is a real difference in the soil uptake between plants.

172. If observations on dietary levels are available for most of the deposition period, P_{2s} can be estimated directly by means of the relation

$$P_{2s} = \frac{\int_{-\infty}^{t} C(\tau)d\tau}{F(t)} + \frac{\int_{t}^{\infty} C'(\tau)d\tau}{F(t)}, \quad (76)$$

where C' is the part of the dietary level due to deposition before time t. The first term to the right will be called $P_{2s}(t)$. Observations on total diet are nowhere available for the whole period of interest, but they can be inferred from observations on body content, as the integrated body content over a reasonably long time is directly proportional to the dietary intake (paragraph 182). For example, Gustafsson and Miller[109, 316] give the integrated dietary intake of caesium-137 for the years 1961-1967 in the Chicago area as 180 pCi y $(gK)^{-1}$. The total uptake can then be estimated by multiplying this value by the ratio between the integrated body levels in the years 1953-1967 and the levels in the period 1961-1967, giving 275 pCi y $(gK)^{-1}$. The total mean deposition of caesium-137 in Chicago up to 1967 was about 85 mCi km^{-2}, and thus $P_{2s}(1967) = 3.25$ pCi y $(gK)^{-1}$ per mCi km^{-2}.

173. To estimate the second term to the right of equation (76), some assumptions regarding the long-term uptake must be made. It is generally assumed that the dietary level caused by a given deposit decreases with time at least at a rate corresponding to the radio-active decay. An upper limit to the value is thus obtained by multiplying C(67) by the radio-active mean life T_m which, with the Chicago data, gives a value of 4.4 for the second term so that $P_{2s} = 7.65$ pCi $(gK)^{-1}$ per mCi km^{-2}.

174. Since a considerable part of the 1967 dietary levels was due to uptake from caesium-137 deposited in the years 1965-1967, this method over-estimates the second term. In the following paragraphs, an estimate of the proportion of the dietary level in 1967 resulting from deposition in 1965 and earlier will be made, taking into account the special deposition pattern during the years 1964-1967. The integrated dietary level due to deposition before 1965 can then be obtained by extrapolating this proportion. As the cumulative deposit increased very little during the period 1965-1967, this extrapolated term can be used as an estimate of

$$\int_{1968}^{\infty} C'(\tau)d\tau.$$

175. The ratio between the dietary levels in 1966 and 1967 can be written

$$\frac{C(66)}{C(67)} = \frac{L(66) + K(2)\,F_r(64) + K(1)\,F_r(65) + K(0)\,F_r(66)}{L(67) + K(2)\,F_r(65) + K(1)\,F_r(66) + K(0)\,F_r(67)}. \quad (77)$$

where $L(66)$ is the uptake in 1966 due to deposition in 1963 and earlier and $L(67)$ the uptake in 1967 from deposition in 1964 and earlier. It will be assumed that these terms are directly proportional to the cumulative deposit in 1963 and 1964, respectively. The annual deposit in the northern hemisphere decreased by about 50 per cent per year[110] from 1964 to 1967. The fact that

$$\frac{F_r(64)}{F_r(65)} \approx \frac{F_r(65)}{F_r(66)} \approx \frac{F_r(66)}{F_r(67)} \qquad (78)$$

implies that

$$\frac{C(66)}{C(67)} \approx \frac{F_d(63) + k[F_r(64) + F_r(65) + F_r(66)]}{F_d(64) + k[F_r(65) + F_r(66) + F_r(67)]}, \qquad (79)$$

where k is a constant reflecting the rate of uptake from comparatively fresh deposit. In order to avoid the lag effects discussed in paragraph 171, milk rather than total diet was chosen to estimate k.

176. When the pertinent deposition and milk data for the United States are inserted in equation (79), it is found that $k = 33$, implying that somewhat less than 20 per cent of the milk level in 1967 was due to deposition before 1965. The future dietary content due to deposition before 1965 can thus be estimated as $0.2\ C(67)\ T'_m$, where T'_m is the effective mean residence time in soil. The sum of this term and the observed integrated dietary content up to 1967 gives an over-estimate of the total integrated dietary content due to deposition before 1965, as the effect on diet during the years 1965-1967 from deposition in this period is included. As the integrated deposit increased very little between 1965 and 1967, this over-estimate is small, however. P_{23} is obtained by dividing the total integrated dietary content thus obtained by the integrated deposit at the end of 1964. The pessimistic assumption that T'_m is equal to the radio-active mean life (forty-four years) gives an estimate of $P_{23} = 4.1$ pCi y $(gK)^{-1}$ per mCi km^{-2}.

177. A fairly large number of observations on the body content of caesium-137 are available, and the dose commitment can then be estimated, without knowledge of P_{23}, from the ratio $P_{23}/P_{23}(t)$ (paragraphs 172 and 186). Since

$$\frac{P_{23}}{P_{23}(t)} = \frac{\int_{-\infty}^{\infty} C'(\tau)d\tau}{\int_{-\infty}^{t} C(\tau)d\tau}, \qquad (80)$$

this ratio can be estimated for different regions in the northern hemisphere, using, for example, milk data and the method indicated in paragraphs 172 to 174. This method has the advantage that information on local deposition is not required.

(c) *Metabolism of caesium-137 in the body*

178. Caesium-137 ingested by man is rapidly distributed in the body, about 80 per cent being deposited in muscle and 8 per cent in bone.[100] About 10 per cent is rapidly excreted, and the remainder is excreted at a slower constant rate. The observed half-life in adults varies between less than fifty and more than 200 days and seems to depend on body weight, sex and dietary habits.[111, 112] Even within a relatively homogeneous group, the variability in half-life is considerable.[113] The half-life in children is shorter than in adults and is of the order of ten days for new-born infants.[100] Based on published data, McCraw[114] gave the empirical equation $T_{\frac{1}{2}} = 12.8\ (u^{\frac{1}{2}} + e^{-u})$ days, where u is age in years. There has been some indication that a small part of caesium might be fixed in bone with long residence time,[109] but no quantitative observations have been reported.

179. The average body content of caesium-137 in a population at a given time varies with individual values of the biological half-life and with dietary habits. The observed caesium-137 levels (in pCi $(gK)^{-1}$ are 20-30 per cent lower in women than in men.[115-119] Levels in children are, as a rule, lower than in adults.[109, 116, 117] For estimating the dose commitment, it will be assumed that the caesium-137 level (in pCi $(gK)^{-1}$) in children is the same as in adults, an assumption which probably results in a small over-estimate of the population average.

180. Although the most accurate determinations of caesium-137 body burdens are by whole-body counting, this method has limitations, as most body counters are immobile. For that reason, measurements on human blood, urine, etc. may serve as a useful supplement to whole-body counting in regions where representative whole-body measurements are not feasible. Such methods also make it possible to use pooled samples from a large number of individuals, and this may be important in regions where there is reason to suspect large variations due to unknown ecological factors.

181. The relation between caesium-137 concentration in blood and body burden has been studied by Yamagata[120] who has also made an extensive survey of body burdens using blood samples.[121, 122] Recently a study by Jaakkola *et al.*[123] has shown a very good correlation between body burden expressed in nCi $(gK)^{-1}$ and blood concentration and a much poorer correlation with caesium-137 concentrations in twenty-four-hour urine samples. The results indicate, however, that pooled urine samples from at least twenty individuals give a reasonable estimate of the average body burden. These results are confirmed by similar investigations made by Ramzaev *et al.*[125] The caesium-137 concentration in human hair has also been found to be well correlated with body content.[126, 318]

(d) *Transfer from diet to body*

182. The short residence time of caesium in the human body (T''_m) implies that the ratio between integrated body content and total dietary intake over some extended period of time (more than, say, two years) will be a good estimate of the transfer coefficient P_{24}, that is,

$$P_{24} = \frac{\int_{-\infty}^{\infty} Q(\tau)d\tau}{\int_{-\infty}^{\infty} C(\tau)d\tau} \approx \frac{\int_{t_1}^{t_1+\Delta t} Q(\tau)d\tau}{\int_{t_1}^{t_1+\Delta t} C(\tau)d\tau}, \qquad (81)$$

when $\Delta t \geqslant 2$ y.

183. The coefficient P_{34} can be estimated directly, using data from the United States[103, 109] and Denmark.[124] Expressed in picocuries of caesium-137 per gramme of potassium, the integrated body content of adults in the United States during the years 1961-1967 was 500 pCi y $(gK)^{-1}$ and the corresponding dietary intake 180 pCi y $(gK)^{-1}$ so that $P_{34} = 2.8$. For Denmark, the integrated body content during the years 1963-1967 was 533 pCi y $(gK)^{-1}$ and the dietary intake 184 pCi y $(gK)^{-1}$, giving $P_{34} = 2.9$. In this case, P_{34} can be regarded as dimensionless.

184. Alternatively, body contents and dietary intakes can be expressed in terms of total activity. Because the integrated body content, when so expressed, is equal to the total dietary intake multiplied by the fractional intake f_1 and by the caesium-137 mean life in the body T''_m,

$$P_{34} = f_1 T''_m \qquad (82)$$

and is thus expressed in units of time. Since fractional intake is close to one,[71] P_{34} is close to the mean residence time in the body. Taking the total content of potassium in the body as 140 grammes and a yearly intake of 1,400 grammes, and using the same data as in the previous paragraph, the values of P_{34} then become 0.27 and 0.31 year for the United States and Denmark, respectively, corresponding to a mean biological residence time of about 100 days. The value of the transfer coefficient thus obtained differs from that obtained in the previous paragraph by the ratio of the potassium body content to the potassium yearly intake or by approximately 0.1 y^{-1}.

185. When observations on total deposit and integrated body burdens are available, numerical estimates of the factors P_{23} and P_{34} are not necessary if the body can be assumed to be in equilibrium with the diet, as in that case the dietary step can be bypassed and the deposit linked to body burden by means of a transfer coefficient P_{234}. In the Committee's 1964 and 1966 reports, P_{234} was estimated from the following equation relating body burden and deposit:

$$Q(t) = P_r F_r(t) + P_{2c}\,(F_r(t-1) + F_r(t-2)). \qquad (83)$$

where P_r and P_{2c} were empirical constants. This equation is analogous to equation (75) and

$$P_{234} = P_r + 2P_{2c}. \qquad (84)$$

186. A more direct estimate of P_{234} can be obtained from

$$P_{234} = \frac{\int_{-\infty}^{\infty} Q(\tau)d\tau}{F(\infty)} = \frac{P_{23}}{P_{23}(t)} \frac{\int_{-\infty}^{t} Q(\tau)d\tau}{F(t)}. \qquad (85)$$

187. The United States data discussed in paragraphs 172 to 175 give, as a conservative estimate,

$$P_{234} = \frac{4.1}{3.25} \frac{744}{85} = 11 \text{ pCi y } (gK)^{-1} \text{ per mCi km}^{-2}, \qquad (86)$$

which is consistent with the value obtained by multiplying P_{23}, as given in paragraph 176 by P_{34} as obtained in paragraph 183.

188. A study of the variation of P_{234} in different parts of the northern hemisphere can be made by comparing integrated body burdens. As, in the northern hemisphere, the deposition rates have varied fairly uniformly with time and as body burdens up to 1967 have mainly been due to short-term uptake, the ratios between body burdens in different parts of the hemisphere in the same time periods should be directly proportional to $F(67)\,P_{234}(67)$.

189. Body burdens in different regions and ratios relative to Gustafsson's and Miller's values are given in table VI from which it is seen that, with the exception of the regions discussed in paragraph 168, the ratios in the northern hemisphere lie between one and two with most values around 1.5, the only exception being Japan with a value of 0.6. It is notable that the ratios in northern Europe tend to increase at the end of the period, indicating that the long-term contribution is somewhat higher than in the United States. This increase is modest, however, and it seems reasonable to assume that the long-term contribution after 1967 is of the order of 25 per cent of the total, as in the United States. Studies of the dietary intake in the different parts of the Soviet Union[127, 128] indicate that the levels in the Moscow and Leningrad areas, from which body burdens have been reported, are reasonably well representative of the entire Soviet Union.

(e) *Dose-rate factor*

190. According to Spiers,[100] a caesium-137 body content of 1 pCi $(gK)^{-1}$ gives a dose rate of 18 μrad y^{-1} for a man weighing 70 kilogrammes and 15 μrad y^{-1} for a child weighing 8 kilogrammes. If the caesium-137 body content is expressed as pCi $(gK)^{-1}$, the dose-rate function $g(u)$ is thus approximately independent of age, and it will be assumed that

$$P_{45} = 18 \text{ } \mu\text{rad y}^{-1} \text{ per pCi } (gK)^{-1} \qquad (87)$$

which, combined with the estimate of P_{234} from the United States data, gives

$$P_{2345} = P_{234}P_{45} = 0.20 \text{ mrad per mCi km}^{-2}. \qquad (88)$$

(f) *Subarctic regions*

191. Caesium-137 levels in the food-stuffs produced in subarctic regions are generally higher than those expected from the amounts of the nuclide deposited per unit area and are especially high in reindeer and caribou meat, as well as in fish from lakes with water low in mineral content.[129] The body burdens of caesium-137 in individuals eating large quantities of reindeer or caribou meat are more than ten times higher than the local population average,[130-132] as shown in table VI.

192. Levels of caesium-137 in reindeer and caribou are high because the lichens, which are an important food for these animals during winter, effectively entrap and retain a substantial proportion of the deposit falling onto them. The apparent half-life of caesium-137 in lichens due to grazing and leaching varies from 2.5 to fifteen years[133-135] so that estimates of the dose commitment for these regions are uncertain. Miettinen and Rahola[131] have calculated average integrated body burdens of about 30 nCi y $(gK)^{-1}$ for Finnish Lapps (reindeer breeders) during the years 1961-1968. Assuming an apparent half-life of between 2.5 and fifteen years, the long-term contribution after 1968 is from 12 to 75 nCi y $(gK)^{-1}$. Thus, the total integrated body

burden should be from 40 to 100 nCi y $(gK)^{-1}$, or about 100 times the average for the northern hemisphere.

3. *External radiation*

193. The exposure from gamma-emitting nuclides deposited on the ground was discussed extensively in the Committee's 1962 and 1966 reports, and the methods used earlier for estimating the corresponding dose commitment are still valid.

194. Theoretical and experimental studies on the transmission of gamma radiation from radio-active deposits make it possible to calculate the resulting air dose, provided the properties of the ground and the distribution of radio-activity in the top layer are known.[136-139] However, as this information is largely unavailable, estimated air doses are only approximate. No new data regarding shielding by buildings and screening by the human body warrant any change in the Committee's earlier estimate[140] of a combined shielding and screening factor of 0.2.

195. The effect of the radio-activity distribution in the top layer on the dose-rate conversion factor has been assessed for the case in which the activity decreases exponentially with depth.[137-139] When the relaxation length l (which corresponds to the depth at which the activity has decreased by a factor of e) increases from zero (i.e., plane source) the dose-rate factor initially decreases rapidly but subsequently rather slowly. When l increases from 1 to 3 centimetres, the dose-rate factor for caesium-137 decreases from 60 to 40 per cent of the plane-source value.[137] From such calculations and studies of the actual distribution,[141, 142] it can be deduced that ground roughness and weathering result in a reduction factor of from one to 0.3 as compared to a plane source.

196. As the short-lived nuclides deliver most of their dose contribution within a relatively short period of time, no reduction factor for soil penetration is required. As regards caesium-137, the main dose contribution occurs after the nuclide has penetrated into the soil. In order to take account of this, a soil shielding factor is applied for caesium-137. The value of this factor is taken to be 0.5. The dose-rate factors given by Beck[138] are used (table XVI). The largest contribution to the dose commitment from external radiation comes from caesium-137. As the $^{137}Cs/^{90}Sr$ ratios in deposit are fairly constant, the caesium-137 external dose commitment can be estimated from either caesium-137 or strontium-90 deposition data.

197. Measurements of air doses due to deposit from nuclear explosions have been reported from Japan,[143, 144] the United Kingdom[145] and Sweden.[146] The yearly mean exposures, ranging from 4 to 12 milliroentgens in Japan, from 4 to 6 milliroentgens in the United Kingdom and from 6 to 9 milliroentgens in Sweden, have not varied appreciably between 1965 and 1967. In Japan, comparatively high exposures were observed during the period December 1966-January 1967, presumably due to fresh debris from tests in central Asia.

198. Estimates of external doses based on deposit measurements have been reported from Argentina[15] and Australia.[17-19] In Argentina, doses to gonads and bone marrow from short-lived nuclides deposited after the 1966, 1967 and 1968 tests in the south Pacific were estimated to have been 4.9, 0.9 and 1.3 millirads, respectively. In Australia, the corresponding doses were well below 1 millirad.

199. While deposition of shorter-lived nuclides during the years 1965-1967 was all due to tests carried out in that period, that of the longer-lived nuclides included a contribution from earlier tests which cannot easily be isolated and which have already been included in the estimate of the external dose commitment given in the 1966 report. The Committee estimates that the external global dose commitment due to short-lived nuclides from tests between 1965 and 1967 is, at most, 2 per cent of the external dose commitment from tests up to 1964.

4. *Carbon-14*

200. Because carbon-14 circulates in nature and its radio-active half-life is long compared with that of the other long-lived nuclides, strontium-90 and caesium-137, the dose from carbon-14 will be received over a very much longer period of time. It is therefore convenient to consider the dose commitment due to carbon-14 in two ways, namely, the total dose commitment itself and that fraction of it which will be delivered up to the year 2000, when most of the dose commitment from the other long-lived nuclides will have been delivered. It is the numerical value of the latter fraction which is usually added to the dose commitments due to the other nuclides to obtain the over-all dose commitment from weapons tests so far carried out, but it must be remembered that there will be a further, and larger, contribution from carbon-14 which will be delivered after the year 2000.

201. Most of the carbon-14 produced by nuclear explosions has been injected into the stratosphere where naturally produced carbon-14 also originates. Transport processes are thus essentially identical for natural and artificially produced carbon-14. If it is assumed that present levels of natural carbon-14 on earth reflect a steady-state condition and that the carbon balance will not change appreciably in the future, it is possible to estimate the dose commitment without any specific assumptions regarding transport processes, population structure, etc. by means of the expression

$$D_p(\infty) = \gamma_0 \frac{W}{B} \cdot \qquad (89)$$

where γ_0 is the dose rate due to natural carbon-14, B is the production rate of natural carbon-14 and W is the amount of artificially produced carbon-14.[67]

202. The exchange processes determining the biospheric levels are characterized by a rapid exchange with time constants of the order of a few years at most between different parts of the atmosphere, biosphere and ocean-surface layer. The transfer into deep ocean and humus is a slower process with time constants of the order of tens of years, and the back-transfer to the atmosphere is still slower with time constants of many hundreds of years.[147, 148] After a few years, the atmospheric and biospheric levels due to an atmospheric injection will thus decrease at a rate mainly determined by the transfer to deep ocean and humus, and the effect of a back-transport will be quite small, at least during the first fifty years. This is the situation obtaining now, since no significant additions to the artificial carbon-14 inventory have been made since 1962.

203. Quantitative studies of the transfer processes usually rely on compartment models with first-order kinetics. Complicated models have been applied,[149-151] but, for the purpose of estimating the dose commitment up to the year 2000, a model with four compartments

is sufficient: (*a*) stratosphere: (*b*) troposphere and biosphere; (*c*) ocean-surface layer; and (*d*) deep ocean and humus.[152] The errors introduced by using this simplified model are small compared to the errors due to uncertainties in estimates of the exchange coefficients.

204. The exchange of artificially produced carbon-14 between different parts of atmosphere and the oceans has recently been studied by Nydal,[149] who estimated the stratosphere-troposphere exchange coefficient to be 0.5 y^{-1}, in agreement with earlier estimates.[152] He further found a mean residence time of four years in the troposphere, a value also obtained by Young and Fairhall.[150] From estimates of the net production rate of carbon in land plants,[153] it can be concluded that the largest part of the carbon dioxide in the atmosphere is taken up by the oceans.

205. Estimates of the rate of uptake by deep ocean and humus are, at present, mainly based on observations of the natural carbon-14 balance.[147,148] The exchange coefficients thus derived refer to well mixed compartments, and it cannot be assumed that they are quantitatively applicable in the present connexion.

206. When the exchange coefficients discussed in paragraphs 203 to 205 are applied to the four-compartment model, it follows that an injection of 10^{27} atoms of carbon-14 in the stratosphere leads to a concentration in the troposphere (expressed in per cent of the natural level) of

$$l(t) = 0.16\, e^{-0.00012t} + 1.96\, e^{-0.029t} + 2.84\, e^{-0.35t} - 4.96\, e^{-0.68t}, \qquad (90)$$

where t is the time after injection in years. The first term allows for radio-active decay. The time constants in the last two terms of this expression are mainly determined by the rapid exchange processes in atmosphere, biosphere and ocean-surface layer, whereas the time constant in the second term to the right is determined by the slower processes discussed in paragraph 205.

207. By the end of 1967, no major atmospheric injections of carbon-14 had occurred in four years. It is found from equation (90) that the second term to the right represents about 80 per cent of $l(t)$ when t is between four and forty years, and the approximate integrated tropospheric level for the years 1968-2000 is, therefore, obtained by assuming that $C(t)$ decays with a time constant 0.029 y^{-1} in this period. Thus,

$$\int_{1968}^{2000} l(t)dt \approx C(1967) \int_{0}^{32} e^{-0.029t}\, dt = 21\, l(1967) \qquad (91)$$

208. As was pointed out in paragraph 205, the exchange coefficients determining the time constant 0.029 are tentative. The integrated tropospheric level is, however, not very sensitive to the value of the time constant. If its true value is in the range 0.01-0.06, it is found that

$$\int_{1968}^{2000} l(t)dt = (20 \pm 7)\, C(1967). \qquad (92)$$

209. The integrated tropospheric concentrations up to 1967, inclusive, can be estimated from data summarized in the Committee's 1964 report[152] and by Nydal[149] (figure 20) to be 510 and 390 per cent year of natural carbon-14 in the northern and southern hemispheres, respectively. In both hemispheres, the concentrations in 1967 were about 65 per cent of the natural level. Thus, the integrated level up to the year 2000 is estimated to be about $510 + 21 \times 65 = 1{,}875$ in the northern hemisphere and 1,750 in the southern hemisphere, or about 1,800 per cent year of carbon-14 globally.

210. As the exchange between tropospheric air, food-producing plants and land animals is rapid, human body levels have followed tropospheric levels with a delay of one to two years.[154, 155] Measurements on human blood and hair indicate that equilibrium has been virtually established since 1965[156] (figure 8), and it can thus be assumed that the integrated body burden up to the year 2000 is the same as the integrated tropospheric content. The dose commitment up to the year 2000 is thus obtained from equation (92) by multiplying by the dose-rate constant γ_0.

211. The dose rate due to the natural carbon-14 produced per year is 0.7 mrad y^{-1} in bone marrow and soft tissue and 0.9 mrad y^{-1} in cells lining bone surfaces.[100]

5. *Iodine-131*

212. Iodine-131 has a short radio-active half-life so that its presence in the biosphere is important only during the first few months immediately following a nuclear explosion. This means that appreciable mixing does not occur before deposition and that the actual fall-out pattern depends very much on the weather during the first week or so following the explosion. Because deposition patterns are so variable and unpredictable, doses can only be calculated if the levels of the nuclide in food are measured directly or if the local transfer coefficients and deposit are known. Since these are often not available from large areas of the world, it is not possible to estimate dose commitments on the global scale but only those to local groups of persons whose food supplies have been adequately monitored.

213. If dose commitments are required, it is essential to have ready a monitoring system whereby representative dietary samples can be obtained and analyzed rapidly. In those areas where milk is a major dietary component, it has been found that, within a specified region, there is usually a strong correlation between the concentration of barium-140 in ground-level air and iodine-131 concentration in milk. Since it is comparatively simple to obtain air samples, such a measurement can be used to trigger full milk sampling systems.

(a) *Iodine-131 in food chains*

214. Where it is a major dietary component, milk dominates as a source of iodine-131 ingestion. In areas where little milk is consumed, the main source of iodine-131 intake is probably vegetables.[64, 213] Once deposited on grass, iodine is removed by various processes such as cropping, leaching and volatilization. Several studies have indicated an effective half-life of three to six days.[157] The efficiency of transfer from grass to milk depends on many factors associated with local farm practices. During winter, transfer will obviously be negligible in areas where cows eat stored feed. Breed of herd, season, density of herbage and milk yield may affect the transfer appreciably.[64, 158, 159]

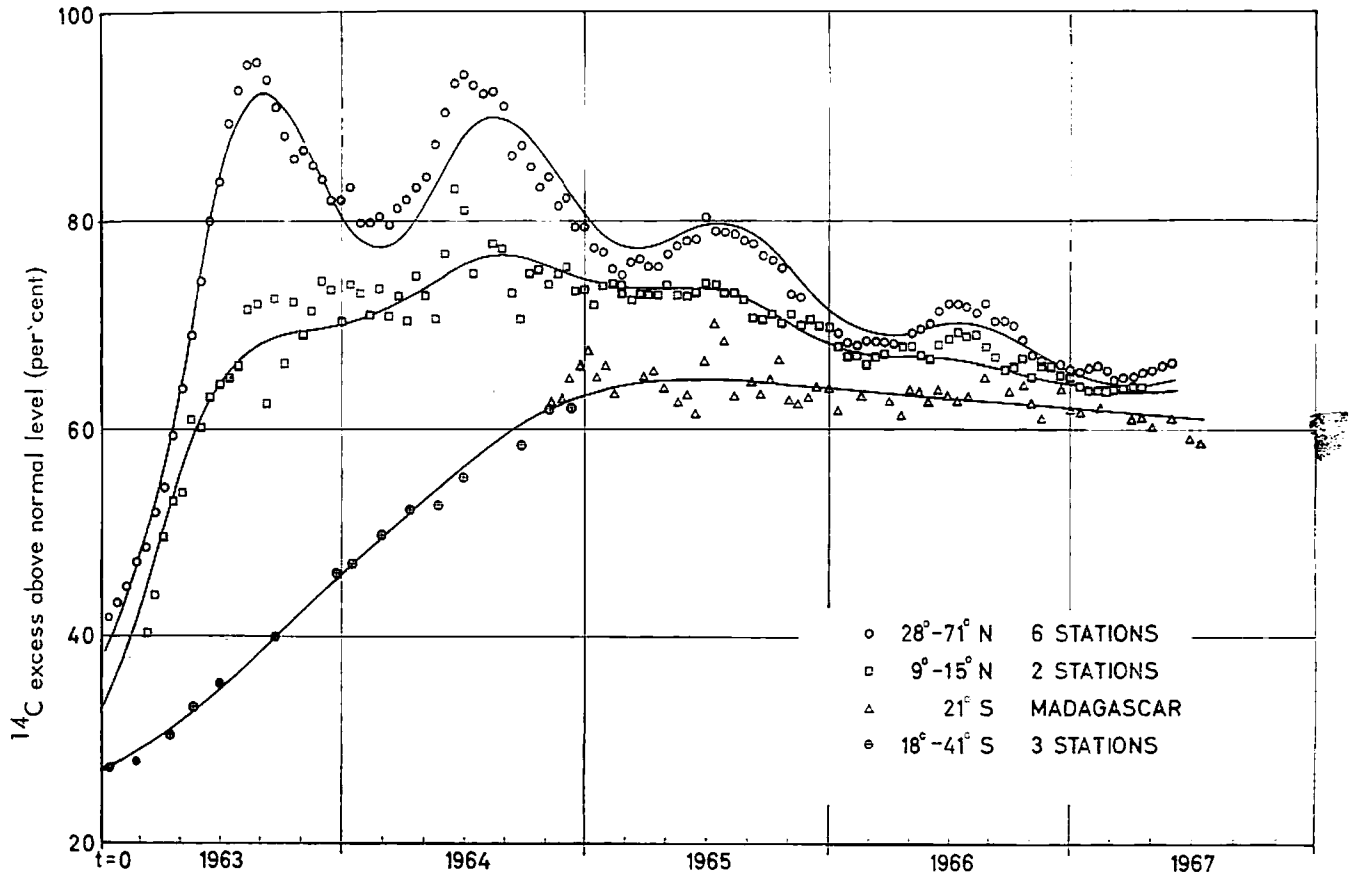


Figure 20. ^{14}C variation in the troposphere[149]

(b) *Metabolism of iodine-131 in the body*

215. Iodine-131 is concentrated in the human thyroid which receives a dose many orders of magnitude greater than any other organ.[100] For a given dietary intake, the resulting dose to the thyroid is at least ten times higher in six-month-old infants than in adults, although the total iodine-131 content of the thyroid is about the same.[160-162]

(c) *Dose-rate factor*

216. In the Committee's 1964 report,[163] it was estimated that an integrated milk level of nCi d l^{-1} results in a thyroid dose of 11.5 millirads to children one to two years of age, in close agreement with later estimates. Corresponding mean doses for individuals in age groups zero to ten, ten to twenty and twenty to seventy years of age are, according to Neill's and Robinson's data,[162] 6.1, 2.5 and 0.7 millirads, respectively.

6. *Other nuclides*

217. Relatively large amounts of iron-55 were produced in the nuclear test series during 1961 and 1962. As iron is readily transferred in the biosphere and taken up by man, relatively high activity levels have been observed in the subsequent years. A number of investigations on iron-55 in food chains and in man have been reported.[164-170] Although the body burdens are comparable to those of caesium-137, the resulting dose rates are far smaller since the dose-rate factor for iron-55 is quite small.[165]

218. Studies on other nuclides produced by nuclear explosions, such as sodium-22, manganese-54, krypton-85, plutonium-239, and tritium, indicate that the internal dose commitments due to these nuclides are of minor importance.[171-174]

D. Dose commitments from external and internal contamination

1. *Introduction*

219. For the purpose of estimating dose commitments, particularly from internally deposited caesium-137 and strontium-90, the world population is divided into three groups:

I(*a*). *Populations living in regions from which a relatively large amount of data on contamination by these long-lived nuclides is available and where transfer processes are sufficiently well understood to make possible reasonably reliable predictions of future levels.* The regions included are those in which the principal source of caesium-137 and strontium-90 in the diet is dairy produce, such as western Europe and North America in the north temperate zone and Argentina, Australia and New Zealand in the temperate zone of the southern hemisphere.

I(*b*). *Populations living in regions in the northern temperate zone from which a relatively large amount of environmental data is also available but where some transfer processes are different from those in* I(*a*). These regions include parts of the Soviet Union and other areas of eastern Europe in which the principal source of caesium-137 and strontium-90 in diet are whole wheat and rye. This group also includes the

population of Japan which differs from the eastern European populations insofar as rice and vegetables are the principal sources of strontium-90 and caesium-137.

II. *Populations in the remaining regions of the world from which almost no environmental data are available and little is known about transfer processes through food chains.* For these regions, it is thus necessary not only to predict future levels but also to estimate past levels. These regions include, in particular, the tropical and subtropical belt.

220. In addition to these broad population groups, there are substantial groups of individuals for whom the dose rates may be much higher than typical values for the temperate zone because of special climatic and dietary factors. An important example is that of the arctic and subarctic regions where people include reindeer and caribou meat and fresh-water fish in their diets. As they are a relatively small fraction of the world's population, the enhanced doses that they receive do not contribute significantly to the world-wide dose commitment.

221. The dose commitment due to carbon-14, on the other hand, does not depend significantly on dietary and social habits, and, since the deposit of carbon-14 is more or less uniform over the globe, it will be equal for all populations.

222. Dose commitments for the population belonging to group I(*a*) will be calculated first, using equation (16) and the values of the transfer coefficients relevant to each case, as estimated in the preceding paragraphs. The special problems arising in the case of populations belonging to groups I(*b*) and II will then be considered separately.

2. *Distribution of world-wide deposit of long-lived radio-nuclides*

223. The distribution of deposit over the surface of the earth is shown in table XVII. The average integrated deposit of strontium-90 in the north temperate latitudes to the end of 1967 is about 65 mCi km^{-2}, whereas that of caesium-137, obtained by multiplying the value for strontium-90 by 1.6 (paragraph 20), is 104 mCi km^{-2}. The corresponding values in the south temperate latitudes are 14 mCi km^{-2} and 22 mCi km^{-2} for strontium-90 and caesium-137, respectively.

3. *Dose commitments to group I(a) population*

(a) *Internal dose commitments*

(i) *Strontium-90*

224. The following values of the transfer coefficients are used

(*a*) P_{23} = 9 pCi y (gCa)$^{-1}$ per mCi km^{-2} (paragraph 140)

(*b*) P_{34} (vertebrae) = 0.2 pCi y (gCa)$^{-1}$ per pCi y (gCa)$^{-1}$ (paragraph 151)

(*c*) P_{45} (bone marrow) = 0.55 mrad y^{-1} per pCi (gCa)$^{-1}$ (paragraph 158)
P_{45} (endosteal cells) = 1.1 mrad y^{-1} per pCi (gCa)$^{-1}$ (paragraph 158)

Thus we obtain

$D_p(\infty)$ (bone marrow) = 64 mrad in the northern hemisphere
= 14 mrad in the southern hemisphere

$D_p(\infty)$ (endosteal cells) = 128 mrad in the northern hemisphere
= 28 mrad in the southern hemisphere

(ii) *Caesium-137*

225. Since P_{234} P_{45} = 0.2 mrad per mCi km^{-2} (paragraph 190),

$D_p(\infty)$ = 21 mrad in the northern hemisphere
= 4 mrad in the southern hemisphere

(iii) *Carbon-14*

226. The total dose commitment from carbon-14 is estimated from equation (89). The rate of production of natural carbon-14 is 2.6 10^{26} atoms per year, and the amount of carbon-14 injected by tests carried out up to 1967 is 650 10^{26} atoms so that

$$D_p(\infty) = \gamma_0 \frac{650}{2.6} \cdot \qquad (93)$$

Since γ_0 equals 0.7 mrad y^{-1} in bone marrow and soft tissues and 0.9 mrad y^{-1} in cells lining bone surfaces (paragraph 211), the corresponding dose commitments are 180 and 230 millirads, respectively.

227. The fraction of the dose commitments to be received by the year 2000 are obtained from equation (92) and the appropriate values of γ_0, giving 13 millirads to bone marrow and soft tissues and 16 millirads to cells lining bone surfaces.

(iv) *Strontium-89*

228. Internal doses due to strontium-89 are insignificant compared with those from other sources of radiation.

(b) *External dose commitments*

(i) *Caesium-137*

229. From table XVI, the air-dose-rate conversion factor for caesium-137 is 0.04 mrad y^{-1} per mCi km^{-2} so that, taking a mean life of caesium-137 of forty-four years and, as in the 1966 report, a shielding factor equal to 0.2, the dose-rate factor is 0.35 mrad per mCi km^{-2} to gonads, bone marrow and cells lining bone surfaces. The corresponding dose commitments are 36 and 5 millirads in the northern and southern temperate zones, respectively.

(ii) *Short-lived nuclides*

230. The external dose commitment from short-lived nuclides is taken to be equal to that from caesium-137 as found in the 1966 report. The Committee recognizes that this is an approximation that may over-estimate the dose commitment from this source.

4. *Dose commitments to populations of group I(b) and group II*

231. Although, during the period up to 1968, levels of strontium-90 and caesium-137 in diets of eastern Europe (as represented by the Soviet Union and

Poland) have consistently been higher by a factor of between two and three than those in western European diets, the corresponding levels in human tissues have only differed fractionally.

232. Because the difference that this observation implies between the values of the diet-to-tissue transfer coefficients of the two populations is not well understood, there is some doubt concerning predictions of the future time course of the body burdens, if the present disparity between the dietary levels of the two groups continues. However, since future levels must continue to decline, the levels integrated over future time in group I(*b*) populations cannot greatly exceed those predicted for group I(*a*), because the rate of decline of levels in the future cannot be less than that determined by the rate of radio-active decay. The uncertainty is larger for strontium-90 since, for caesium-137, a smaller proportion of the total expected dose is yet to be delivered.

233. In the case of Japan, measured levels of both long-lived nuclides in human tissues have been somewhat lower than those found in the corresponding tissues of populations belonging to group I(*a*) in the northern hemisphere. Thus, the dose commitments for strontium-90 and caesium-137 calculated for group I(*a*) populations living in the northern temperate zone somewhat over-estimate those applicable to Japan. Until better information is available, therefore, the Committee is satisfied that the dose commitments calculated for the northern temperate zone are also applicable without serious error to populations belonging to group I(*b*).

234. It is only possible to speculate about the values of dose commitments to populations belonging to group II. In its previous reports, the Committee had assumed that levels of caesium-137 in human tissues would be proportional to the levels of deposit, though there was no evidence to support this. Body burdens of strontium-90 were assumed to be proportional to levels of contamination in food-stuffs, the latter being estimated from the levels of the deposit using deposit-to-food-stuff transfer coefficients estimated in the temperate latitudes and allowing for the different proportions each foodstuff contributed to the diet. The deposit-to-diet transfer coefficients for both caesium-137 and strontium-90 may be greater in tropical and subtropical areas than in the temperate zones because of differences in climate, soil and agricultural practices. However, in regions belonging to group II, the cumulative deposit is smaller by a factor of between two and ten than it is in the north temperate zone. Thus, even though the deposit-to-diet transfer coefficients for individual foodstuffs may be several times greater than the corresponding values in the temperate zones, it seems unlikely that the levels of contamination in group II dietary components will significantly exceed those observed in group I(*a*). When allowance is made for the different dietary composition, the most pessimistic assumption is that the levels in whole diet will, at most, be as high as those observed in eastern European populations. The Committee believes therefore that the dose commitments estimated for internally deposited strontium-90 and caesium-137 in the northern temperate zone may be taken as reasonably reliable upper limits for the group II population.

235. Estimates of dose per unit deposition due to external sources are based on measurements and parameters appropriate to the north temperate zone and may, because of the effect of different living habits on shielding, be too low for populations living in other areas. However, the maximum error due to this effect cannot exceed a factor of two, and, since accurate data are not available, it will be assumed for present purposes, as in previous reports, that the dose commitment due to external sources is proportional to the integrated deposit.

236. The world-wide average dose commitment from external sources is therefore calculated in the following way. The distribution of the world population and fall-out by latitude is given in table XVII, from which it has been estimated that the mean deposit over the world surface is 26 mCi km^{-2}. Since the population-weighting factor Z is 1.56 (table XVIII), the average deposit of strontium-90 weighted by population is 40 mCi km^{-2} and that of caesium-137, after applying the ratio 1.6 (paragraph 10), 64 mCi km^{-2}. Using the same factors as given in paragraph 227, this corresponds to a dose commitment from external caesium-137 of 23 millirads. The corresponding dose commitment due to short-lived radio-nuclides is also taken to be 23 millirads (paragraph 230).

237. The dose commitments due to internally deposited carbon-14, strontium-90 and caesium-137 to the world population are taken to be the same as those estimated for the north temperate zone (paragraphs 222-228). As noted in paragraph 234, the doses obtained for strontium-90 and caesium-137 are considered to represent upper limits of the dose commitments for those populations that live outside the north temperate zone.

238. Dose commitments estimated for the north and south temperate zones, as well as the average for the world weighted by population are summarized in table XIX.

TABLE I. ANNUAL AND CUMULATIVE WORLD-WIDE ^{90}Sr DEPOSITION[44]

(values in megacuries)

	Annual deposition			*Cumulative deposit*		
	Northern hemisphere	*Southern hemisphere*	*Total*	*Northern hemisphere*	*Southern hemisphere*	*Total*
Pre-1958				1.7	0.6	2.3
1958	0.74	0.31	1.05	2.39	0.83	3.22
1959	1.10	0.19	1.29	3.41	0.99	4.40
1960	0.26	0.17	0.43	3.59	1.14	4.73
1961	0.35	0.19	0.54	3.84	1.28	5.12
1962	1.45	0.31	1.76	5.16	1.55	6.71
1963	2.62	0.33	2.95	7.62	1.84	9.46
1964	1.66	0.44	2.10	9.06	2.21	11.27
1965	0.78	0.36	1.14	9.61	2.51	12.12
1966	0.33	0.21	0.54	9.70	2.65	12.35
1967	0.17	0.11	0.28	9.62	2.69	12.31

TABLE II. ^{90}Sr INVENTORY[54]

(values in megacuries)

	1963			*1964*			*1965*			*1966*			*1967*			
	Mar.	*July*	*Nov.*	*Mar.*	*July*	*Nov.*	*Mar.*	*July*	*Nov.*	*Mar.*	*July*	*Oct.*	*Jan.*	*Apr.*	*July*	*Oct.*
Stratosphere	6.5	5.1	3.8	3.0	2.1	1.7	1.3	0.9	0.8	0.6	0.5	0.4	0.3	0.3	0.3	0.4
Troposphere	0.5	0.2	0.2	0.4	0.3	0.1	0.2	0.1	0.1	0.1	0.1	0	0	0	0	0
Local fall-out	2.4	2.4	2.4	2.3	2.3	2.3	2.3	2.2	2.2	2.2	2.2	2.2	2.1	2.1	2.1	2.1
Global fall-out	7.2	8.7	9.4	9.9	10.9	11.2	11.5	11.9	12.1	12.2	12.3	12.3	12.3	12.4	12.4	12.4
TOTAL	16.6	16.4	15.8	15.6	15.6	15.3	15.3	15.1	15.2	15.1	15.1	14.9	14.7	14.8	14.9	14.9
Corrected for decay to March 1963	16.6	16.5	16.1	16.0	16.1	15.9	16.1	16.0	16.3	16.3	16.4	16.3	16.2	16.3	16.6	16.7

TABLE III. ^{90}Sr AND ^{137}Cs IN MILK

Region or country	^{90}Sr to calcium ratio (pCi g^{-1})				^{137}Cs concentration (pCi l^{-1})				References
	1965	1966	1967	1968	1965	1966	1967	1968	
Argentina	6.5	5.2	5.2	3.8	20	21	11	10	15
Australia	9.2	7	5.3		47	28	20	15	247-250
Austria	31	23			138	70			212,236
Belgium	19	13			73	36			214
Canada	19	13	10	8	108	51	33	25	215-219
Czechoslovakia	18	16							220
Denmark	17	12	8		56	26	14		124,221,222
Faroe Islands	115	73	51		1 100	800	586		202-204
Finland	18	13	10	9	190	143	106	78	208,209
France	28	21	17	14	115	58	29		225,226
	30		15	12	130		34	24	227
Germany—Federal Republic of	24	16	12		107	61			223,224
Greenland	Dried milk imported from Denmark								205-207
Hawaii	7	4.3	3		50	25	9		240
Iceland	80				750				210
India	11	11			24				246,251
Israel	3.3	2.3	2.0		25	14	11		228,229
Italy	19	13			140	80			230
Jamaica	11	9			270	200	184		240
Japan	15	11				56			231,232
Mexico	1.5				55				245
Netherlands	17	15	9		107	43	37		233
New Zealand	12	7.9	6.4	5.2	60	40	31	23	25
Norway	40	28	16	11	360	234	181	146	211
Panama	4.9	4			37	21	22		240
Puerto Rico	8	6	4		42	21	14		240
Sweden		18	13	10	117	71	46	40	234,235
Switzerland	39	28	15		69	28	15		236
Ukrainian Soviet Socialist Republic	10	8							237
Union of Soviet Socialist Republics	16	12	8		78	56			127,239
	20	16	13		215	90	51		185
United Arab Republic	15	13		6					242-244
United Kingdom	19	12	9		98	46	20		65,238
United States	14	11	9		57	29	16		240
Alaska	14	12	6		57	34	20		186
Chicago	12	9	8						240
New York City	19	12	10	9					241
San Francisco	9								240
Venezuela	4.3	4			20	14	9		240

TABLE IV. ^{90}Sr AND ^{137}Cs IN TOTAL DIET

Region, area or country	^{90}Sr to calcium ratio ($pCi\ g^{-1}$)				^{137}Cs daily intake ($pCi\ d^{-1}$)				References
	1965	1966	1967	1968	1965	1966	1967	1968	
Northern hemisphere									
Austria	40	23			231	135			212,236
Denmark	23	14	10		193	79	44		124,221,222
Faroe Islands	56	33	22		880	500	480		202-204
Federal Republic of Germany	36	29	25		132	84			223,224
Finland	34	21			340	260			28
France									
Paris	30	22	19	17					227
Southeast	34	27	22	18					227,252
Greenland	27	15	9		194	89	297		205-207
India (Tarapur)	24				35				251
Israel	22				92				253
Japan (urban)	25	24	18		34	18	14		257
Netherlands	29	21	12		160	87	47		233
Norway	54	38			660	420			28
Sweden	32	22			221	132			28
Ukrainian Soviet Socialist Republic	57	42			221				127
Union of Soviet Socialist Republics	63	40	28		236	147			127,128
United Arab Republic		45		13					242,244
United Kingdom	18	Survey discontinued			106				256
United States	22	16	12		105	55	30		240
Alaska	29	29	16		140				240
Chicago	19	15	12		130				254,255
Hawaii	21	10	6		65	65	35		240
New York City	24	18	17	14	170				241
San Francisco	11	6	5.5	4.3	108				241
Southern hemisphere									
Argentina	9	7	7	5			24	18	15
Australia	11	7	6						249

TABLE V. $^{90}Sr/Ca$ RATIOS IN HUMAN BONE

(number of samples in parentheses)

Region or country	*Year*	*New-born and/ or still-born*	*0-1 year*	*1 year*	*2 years*	*3 years*	*4 years*	*5-19 years*	*19 years*	*Bone type (adults)*	*References*
					Northern hemisphere						
Canada	1965	2.9 (10)	7.4 (77)	8.6 (16)	10.0 (17)	7.5 (23)	6.3 (16)	4.0 (103)	3.1 (71)	V[a]	260
	1966	3.2 (20)	5.7 (151)	6.4 (32)	7.1 (28)	7.0 (17)	5.5 (18)	4.7 (125)	2.6 (15)	V	272
	1967	2.8 (9)	4.0 (141)	5.4 (44)	5.2 (35)	6.2 (20)	5.0 (15)	3.8 (138)	2.6 (59)	V	272
Czechoslovakia	1965	4.0 (37)	5.0 (51)	6.9 (10)	3.5 (5)	4.2 (8)	5.5 (3)	4.8 (56)	2.2 (141)	V	220
	1968								1.7 (54)	V	73
Denmark	1965	2.9 (14)				6.6 (25)		4.1 (31)	2.7 (23)	V	221
	1966	1.9 (19)	2.9 (34)	2.6 (2)	3.3 (3)	4.6 (2)	4.4 (2)	3.5 (35)	2.6 (32)	V	222
	1967	1.8 (22)				2.7 (32)		2.5 (31)	2.1 (42)	V	124
	1968	1.2 (10)				2.5 (51)		2.3 (19)	1.9 (34)	V	58
Finland	1965	4.8 (1)				5.1 (19)		2.9 (41)	0.65 (47)	T[b]	258
	1966	2.1 (2)				4.1 (22)		2.4 (46)	0.65 (78)	T	258
	1968	1.7 (10)				2.1 (14)		2.4 (23)	0.72 (131)	T	258
Federal Republic of Germany	1965	2.5 (92)	6.2 (10)			5.5 (9)		2.7 (13)	1.1 (43)	T	261
	1966	2.1 (76)	5.5 (4)			5.1 (9)		2.7 (14)	1.0 (47)	T	261
	1967	1.5 (116)	2.9 (15)			3.6 (9)		2.9 (36)	0.9 (62)	T	261
France	1965	2.92 (32)	6.8 (47)			7.6 (13)		3.3 (35)	2.2 (69)	V	179
	1966	2.21 (21)	4.8 (46)			5.3 (13)		3.2 (56)	2.1 (56)	V	179
Japan	1965	2.2 (12)				5.1 (13)		2.5 (27)	1.0 (20)	R[c]	262
	1966	1.9 (8)				3.3 (35)		2.1 (27)	0.8 (23)	R	262
Norway	1965	5.4 (20)	11.4 (11)			11.8 (3)		7.4 (9)			259

	1966	3.0 (22)	6.3 (10)			10.0 (9)			5.6 (9)	3.1 (4)	V	259
	1967	2.8 (17)	4.4 (14)			6.5 (10)			5.7 (8)	4.3 (10)	V	259
	1968	2.9 (34)	4.2 (9)			6.2 (5)			5.0 (9)	3.7 (10)	V	259
Poland	1965		6.8 (4)	4.0 (3)				3.5 (3)	5.4 (4)	2.5 (23)	V	263
	1966		5.0 (6)	6.1 (2)					4.1 (3)	2.9 (67)	V	263
United Kingdom	1965	2.5 (101)	7.1 (86)	9.1 (11)	6.1 (8)		6.8 (8)	4.5 (5)	2.7 (58)	0.9 (23)	F[d]	264
	1965	3.0 (2)				6.8 (20)			3.2 (5)	1.9 (48)	V	264
	1966	2.2 (90)	4.9 (74)	6.5 (8)	5.6 (6)		4.8 (9)	4.8 (7)	2.6 (74)	2.2 (53)	V	264
	1967	2.2 (87)	3.3 (60)	4.8 (12)	4.1 (7)		2.3 (1)	3.2 (6)	2.1 (74)	1.6 (108)	V	266
Union of Soviet Socialist Republics	1965	3.5 (99)	5.0 (39)			5.8 (16)			3.7 (1 559)	1.6 (546)	Normalized to whole skeleton[e]	178
	1966	2.5 (132)	4.1 (81)			5.5 (48)			4.0 (1 389)	1.6 (1 032)		178
	1967	2.0 (94)	3.0 (51)			4.3 (45)			2.5 (416)	1.6 (266)		178
	1968	1.7 (37)	2.6 (7)			3.7 (16)			2.10 (871)	1.0 (165)		178
United States												
New York City, N. Y.	1965	2.8 (6)	5.0 (5)	7.0 (3)	7.2 (2)		6.7 (6)	4.1 (2)	3.5 (39)	2.1 (16)	V	268
	1966		4.3 (80)	7.0 (2)	6.2 (3)			5.0 (1)	3.3 (19)	2.1 (22)	V	269
	1967		4.1 (9)	3.2 (5)	3.2 (5)		3.2 (3)	4.0 (4)	2.9 (31)	1.9 (54)	V	270
	1968		3.3 (8)	3.6 (4)					3.1 (42)	1.9 (33)	V	243
San Francisco, Cal.	1965	1.6 (13)	3.3 (13)	3.8 (6)	3.1 (1)		3.0 (3)	1.8 (5)	1.7 (19)	1.2 (30)	V	268
	1966	1.2 (18)	2.3 (14)	3.1 (4)	3.8 (2)		2.9 (4)	2.7 (3)	1.6 (16)	1.2 (9)	V	269
	1967	0.9 (27)	1.6 (19)	1.7 (3)			1.5 (2)	1.9 (2)	1.4 (11)		V	270
	1968	0.7 (20)	1.8 (1)	1.7 (5)					1.4 (14)	1.2 (23)	V	243
All regions	1965		3.9 (22)	4.1 (12)	4.8 (18)		4.3 (15)	3.0 (14)	2.6 (155)	1.8 (60)	V	186
	1966		3.9 (6)	4.1 (14)	4.1 (15)		4.3 (16)	3.2 (16)	2.6 (193)	2.1 (61)	V	186
	1967		1.3 (5)	3.3 (9)	4.6 (7)		3.6 (12)	4.5 (2)	2.7 (93)	1.7 (40)	V	186

TABLE V. $^{90}Sr/Ca$ RATIOS IN HUMAN BONE (*continued*)

(*number of samples in parentheses*)

Region or country	*Year*	*New-born and/ or still-born*	*0-1 year*	*1 year*	*2 years*	*3 years*	*4 years*	*5-19 years*	*19 years*	*Bone type (adults)*	*References*
					Southern hemisphere						
Argentina (littoral area)	1965	1.6	2.0	2.3	2.0	——— 1.7 ———		1.5			15
		(12)	(39)	(8)	(5)	(4)		(12)			
	1966	1.4		2.0	2.2	——— 2.0 ———		1.5	1.6		15
		(26)		(10)	(13)	(12)		(16)	(10)		
	1967	1.5	2.1	2.0	2.7	——— 1.6 ———		1.7			15
		(21)	(30)	(16)	(13)	(15)		(37)			
	1968	1.4	1.5	1.8	2.1	——— 1.9 ———		1.8			15
		(48)	(49)	(15)	(10)	(15)		(42)			
Australia	1965	1.4	2.8	3.4	2.8	2.3	2.5	1.5	0.95	V	247
		(53)	(121)	(23)	(13)	(11)	(9)	(102)	(460)		
	1966	1.5	2.0	2.5	2.7	2.5	2.3	1.5	1.0	V	248
			(171)	(14)	(16)	(7)	(10)	(78)	(381)		
	1967	1.0	1.3	1.7	2.2	1.8	1.7	1.5	1.0	V	249
		(65)	(120)	(18)	(8)	(8)	(9)	(65)	(276)		

[a] V—Vertebrae
[b] T—Tibiae
[c] R—Ribs
[d] F—Femora
[e] Adult vertebrae (Moscow) for years 1965-1968 were 3.1, 2.7, 2.3 and 1.8 pCi $(gCa)^{-1}$, respectively.

TABLE VI. ^{137}Cs BODY BURDENS
$(pCi\ (gK)^{-1})$

A—Body burden

B—Ratio between United States and local values (adjusted, when appropriate, to adult average, assuming the average ratio between male and female values to be 1.3)

Region, area or country	*Latitude*	*Sex*		*1956*	*1957*	*1958*	*1959*	*1960*	*1961*	*1962*	*1963*	*1964*	*1965*	*1966*	*1967*	*1968*	*References*
								Northern hemisphere									
United States average[a]	30–50°N	MF	A	31.5	36.5	47.0	57.0	48.0	32.5	43.0	79.5	140.0	111.5	69.0	41.0		109
Belgium	~50°N	MF	A					50	33	38	95	158	135	87	50	29	273
			B					1.04	1.02	0.91	1.20	1.13	1.21	1.26	1.22		
Canada (Ottawa)	~45°N	MF	A										170				274
			B										1.52				
Denmark	55–60°N	MF	A									185	168	107	74	46	127
			B									1.32	1.51	1.54	1.81		
Federal Republic of Germany	47–55°N																
Karlsruhe		MF	A							28	75	151	114	83	49		117
			B							0.65	0.94	1.08	1.08	1.20	1.20		
Nordrhein-Westfalen		M	A									249	186	128	76		117
			B									1.55	1.45	1.62	1.64		
Finland	~60°N	MF	A								152	211	188	150			275–277
			B								1.91	1.51	1.69	2.18			
France	~50°N	MF	A								118	227	194				278
			B								1.48	1.62	1.74				
Israel	~35°N	M	A													48	279
Italy	40°N	MF	A								107						280
			B								1.35						
Japan	30–45°N	MF	A									93	77	54			281–282
			B									0.58	0.60	0.68			
Norway	~60°N	MF	A										430	290			28
			B										3.85	4.20			
Poland	50–55°N	MF	A								157	164	185		71		263,283
			B								1.98	1.17	1.66		1.73		
Sweden	~60°N	MF	A				74	68	54	45	111	205	187	139	107	74	284,285
			B				1.30	1.42	1.66	1.05	1.40	1.46	1.68	2.02	2.61		
Switzerland	~50°N	MF	A									185	161	92	50		116
			B									1.32	1.44	1.33	1.22		
Union of Soviet Socialist Republics																	
Moscow	~55°N	M	A								181	258					286
			B								2.28	1.84					
Leningrad		MF	A								145	174	142	92	68		115,287
			B								1.83	1.24	1.27	1.33	1.66		
United Arab Republic	~30°N		A												23.5	14.5	288

TABLE VI. ^{137}Cs BODY BURDENS (*continued*)

Region, area or country	*Latitude*	*Sex*		*1956*	*1957*	*1958*	*1959*	*1960*	*1961*	*1962*	*1963*	*1964*	*1965*	*1966*	*1967*	*1968*	*References*
United Kingdom ...	50–60°N	MF	A	32	37	48	58	49	36	35	81	155	150	77	38		289,290
			B	1.02	1.01	1.02	1.02	1.02	1.11	0.81	1.02	1.11	1.35	1.11	0.93		
United Kingdom ...	50–60°N	F	A			55	57	50	33	44	92	149	109	60	33		118
			B			1.32	1.13	1.17	1.15	1.15	1.31	1.21	1.10	0.99	0.92		
United Kingdom ...	56–60°N	M	A										148	89	45		118
			B										1.16	1.12	0.96		
Subarctic regions[b]																	
Alaska (Anaktuvuk Pass)	65–70°N	M	A							3 000	4 500	9 100	6 600	4 900	4 300		291,292
Canada	60–70°N																
(Eastern Arctic Eskimos)		M	A											5 800			293
(Central Arctic Eskimos)		M	A												11 000		293
Finland	65–70°N																
Reindeer breeders, Lapland		M	A							3 600	4 600	8 900	10 300	8 900	6 300	5 900	131
Union of Soviet Socialist Republics	65–70°N																
(Reindeer breeders, Nenets district)		M	A										11 000				132
Southern hemisphere																	
Argentina	30–40°S		A											31	20	16	15
Australia	30–40°S		A										65	42	37	18	294

[a] Average body burdens for the years 1953, 1954 and 1955 were 2.0, 7.0 and 14.5 pCi $(gK)^{-1}$.
[b] Average spring to summer values for groups largely subsisting on reindeer or caribou meat.

TABLE VII. ^{131}I IN MILK AND THYROID DOSES

Region, area or country	Time integral of ^{131}I concentration in milk (pCi d l^{-1})			Integrated thyroid doses to infants (mrad)			References
	1966	1967	1968	1966	1967	1968	
Argentina							
Bariloche	7 602	1 392		88	16		15
Buenos Aires	26 995	4 346	2 477	312	50	29	15
Salta	15 028	1 800		174	21		15
Australia							
Malanda (Highest)	11 000	10 360	4 540	127	120	55	22
Hobart-Launceston (Lowest)	1 500	380	790	17	4	9	22
Chile (Santiago)	4 000			46	9	< 10	14,295
Colombia (Bogota)	400			5	5	< 10	14,295
Ecuador (Quito)	2 500			29		< 10	14,295
Fiji (Suva)	12 600–15 000			146–174			23
Madagascar (Diego Suarez)	13 000		6 500	150	22	80	14,295
New Zealand	1 000			12			23
Peru							
Lima	6 000		4 000	70	23	50	14,295
Tacna						120	
Society Islands (Papeete, Tahiti I.)					55		295
Western Samoa (Apia)	> 7 300			> 84			23

TABLE VIII. RELATIVE DISTRIBUTION OF ^{90}Sr IN ADULT SKELETON

A — samples not necessarily taken from same individuals

Date	Vertebrae / Whole skeleton	Ribs / Whole skeleton	Femur diaphyses / Whole skeleton	Vertebrae / Ribs	Vertebrae / Femur diaphyses	Number of samples	References
1956	3.4	1.5	0.8	2.3	4.3	2	177
1957	1.8	1.1	0.5	1.6	3.6	9	177
1958/1959	2.1	1.4	0.45	1.5	4.7	59	177
1959	—	—	—	2.1	5.6	11	296
1961	—	—	—	1.6	3.1	4	296
1963	—	—	—	1.4	—	A	179
1963	1.5	1.0	0.5	1.5	3.1	A	74
1964	—	—	—	1.4	—	A	179
1965	—	—	—	1.7	—	A	179
1965	—	—	—	1.7	4.7	A	74
1966	—	—	—	1.4	—	A	179
1967	1.9	0.75	0.6	2.5	2.9	40	74
1968	—	—	—	—	2.7	54	73

TABLE IX. BONE/DIET OBSERVED RATIOS

Region or country	Observed ratio	References
Australia	0.33	[a]
Canada	0.24–0.26	305
Denmark	0.33	[b]
Japan	0.13–0.16	306,307
Union of Soviet Socialist Republics (Moscow)	0.20	88
United Kingdom	0.23–0.25	308,309
United States	0.18	310
	0.16–0.20	311
Chicago	0.15	312
New York City	0.17	312
San Francisco	0.22	312

[a] Calculated from data published in references 247-249, 297-303.

[b] Stable strontium in diet from reference 176 and in bone from reference 304.

TABLE X. ANNUAL AVERAGE $^{90}Sr/Ca$ RATIOS IN MILK BY COUNTRY OR AREA IN THE NORTH TEMPERATE ZONE

pCi $(gCa)^{-1}$

Year	Country or area										United States of America				
	Canada[218]	Czechoslovakia[220]	Denmark[176]	Federal Republic of Germany[117]	Finland[200]	France[211]	Netherlands[167]	Ukrainian SSR[237]	USSR Moscow[36]	United Kingdom[185]	Whole Country[186]	Chicago[318]	New York City[313]	Salt Lake City[186]	Mean
1955	—	—	—	3	—	—	—	—	—	4	—	—	—	—	3.5
1956	—	—	—	4	—	—	—	—	—	6	—	—	—	—	5.0
1957	—	—	—	6	—	—	—	—	—	6	—	—	5	4	5.3
1958	—	—	—	5	—	—	—	—	—	7	—	7	8	4	6.2
1959	—	—	9	9	—	—	—	—	8	10	—	7	11	6	8.5
1960	—	—	4	7	7	—	—	—	6	6	—	8	8	6	6.5
1961	—	—	4	6	6	—	—	—	4	6	7	6	7	4	5.6
1962	—	—	12	11	13	—	9	—	13	12	11	9	12	8	11.0
1963	26	21	24	26	22	—	25	27	23	26	19	17	26	19	23.2
1964	28	20	25	27	23	—	22	20	18	28	19	16	23	23	22.5
1965	19	18	17	24	18	24	17	11	14	19	14	12	19	17	17.4
1966	13	12	12	16	13	19	15	9	15	12	11	9	12	10	12.7
1967	10	—	9	12	10	14	9	—	8	9	9	8	10	5	9.4
1968	8	—	—	—	9	12	—	—	—	—	—	—	—	—	—
												Total 1955-1967			137

TABLE XI. RATIO OF $^{90}Sr/Ca$ RATIOS IN WHOLE DIET AND IN MILK[236]

Country	1963	1964	1965	1966	1967	Mean for 1963-1967
Argentina	1.8	1.5	1.3	1.3	1.3	1.4
Australia	1.1	1.0	0.9	0.9	1.2	1.0
Denmark	1.3	1.7	1.3	1.2	1.2	1.4
Federal Republic of Germany	1.3	1.6	1.7	1.8	—	1.6
Finland	—	—	1.8	1.6	—	1.7
France	—	—	—	1.0	1.3	1.2
Norway	—	—	1.3	1.3	—	1.3
Sweden	—	—	1.4	1.5	—	1.5
United Kingdom	0.9	0.9	1.0	—	—	0.9
United States	1.2	1.4	1.4	1.4	1.5	1.4
Hawaii	1.6	2.2	3.5	2.1	2.0	2.3
India	—	—	—	3.6	—	3.6
Japan	2.1	2.2	2.3	2.3	—	2.2
Union of Soviet Socialist Republics	2.3	3.1	3.7	3.0	—	3.0

TABLE XII. ESTIMATION OF P_{51} FROM BONE MEASUREMENTS IN AUSTRALIA[a]

Year (t)	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Population average $^{90}Sr/Ca$ ratio	.26	.28	.19	.30	.32	.63	.66	.76	.84	1.21	1.26	
Levels integrated to year $t-1$: G_{t-1}		.26	.54	.73	1.03	1.35	1.98	2.64	3.40	4.24	5.45	6.71
Levels integrated from t to ∞: H_t	1.63	1.92	1.22	1.91	2.14	4.45	4.64	5.30	5.83	8.40	8.87	8.31
$G_{t-1} + H_t$	1.63	2.18	1.76	2.64	3.17	5.80	6.62	7.94	9.23	12.64	14.32	15.02
Dietary level integrated to t	4.5	8.3	12.4	17.2	21.6	26.3	32.1	38.5	47.6	58.3	65.5	71.5
P_{51}	.36	.26	.14	.15	.15	.22	.21	.21	.19	.22	.22	.21

[a] From data given in references 247-249, 297-303.

TABLE XIII. ESTIMATION OF P_{34} FROM BONE MEASUREMENTS IN NORTH TEMPERATE LATITUDES[a]

Year (t)	*1954*	*1955*	*1956*	*1957*	*1958*	*1959*	*1960*	*1961*	*1962*	*1963*	*1964*	*1965*	*1966*	*1967*	*1968*
Population average $^{90}Sr/Ca$ ratio	0	0.17	0.28	0.44	0.65	0.70	1.01	1.21	1.32	1.73	2.88	3.33	2.78	2.32	1.92
Levels integrated to year $t-1$: G_{t1}	0	0	0.17	0.45	0.89	1.54	2.33	3.34	4.55	5.87	7.60	10.48	13.81	16.59	18.91
Levels integrated from t to ∞: H_t	0	1.14	1.89	3.00	4.23	5.46	7.10	8.60	9.42	11.95	19.57	23.06	19.91	16.73	13.92
$G_t1 + H_{-t}$	0	1.14	2.06	3.45	5.12	7.00	9.43	11.94	13.97	17.82	27.17	33.54	33.72	33.32	32.83
Levels in diet[b] integrated to t	—	4.90	11.90	19.30	28.00	40.00	49.00	57.00	72.50	104.50	135.30	158.50	175.90	188.10	200.00
P_{34}	—	0.23	0.17	0.18	0.19	0.18	0.19	0.21	0.19	0.17	0.20	0.21	0.19	0.18	0.16

[a] From data given in figure 17.

[b] Dietary levels obtained from milk levels (table X) multiplied by 1.4.

TABLE XIV. VALUES OF $\overline{D}_m/D_0$[a] FOR CORTICAL AND TRABECULAR BONE IN ADULT SKELETON[317]

			Trabecular bone				*Cortical bone*			
Groups of bones	*Basis of calculation*	*Fraction of bone involved*	*Trabecular contribution*	*Mean* $\overline{D}_m/D_0$	*Marrow fraction,* f_m	$f_m\overline{D}_m/D_0$	*Cortical Contribution*	*Mean* $\overline{D}_m/D_0$	*Marrow fraction,* f_m	$f_m\overline{D}_m/D_0$
Hip bone	Hip bone	0.6	0.189	0.1134	0.287	0.0326	0.051	0.0306	0.287	0.0088
Scapulae Clavicles		0.4	0.114	0.0456		0.0131	0.072	0.0288		0.0083
Cranium	Cranium	1.0	0.120	0.1200	0.119	0.0143	0.272	0.2720	0.119	0.0324
Ribs Mandible Sternum	Ribs	1.0	0.138	0.1380	0.114	0.0157	0.136	0.1360	0.114	0.0155
Humeri	Femur	0.53	0.161	0.0853	0.057	0.0049	0	0	0.057	
Femora		0.47	0.134	0.0630		0.0036	0.060	0.0282		0.0016
Vertebrae	Lumbar vertebra	1.0	0.124	0.124	0.423	0.0525	0	0	0.423	0
Sacrum										
						TOTAL 0.1367				TOTAL 0.0666

[a] D_0 is the dose rate to a very small tissue-filled cavity. It is usually taken to be 2.7 mrads y^{-1} per pCi $(gCa)^{-1}$. D_m is the mean dose rate to the bone marrow. Therefore, the bone marrow dose rate factor due to strontium-90 in trabecular bone is $0.1367\ 2.7 = 0.37$ mrads y^{-1} per pCi $(gCa)^{-1}$ and that from strontium-90 in cortical bone is 0.0666 $2.7 = 0.18$ mrad y^{-1} per pCi $(gCa)^{-1}$.

TABLE XV. VALUES OF $\overline{D}_s/D_0$[a] FOR CORTICAL AND TRABECULAR BONE IN ADULT SKELETON[317]

Groups of bones	Basis of calculation	Fraction of bone involved	Trabecular bone: Trabecular contribution	Trabecular bone: Mean $\overline{D}_s/D_0$	Trabecular bone: Endosteal fraction, f_s	Trabecular bone: $f_s\overline{D}_s/D_0$	Cortical bone: Cortical contribution	Cortical bone: Mean $\overline{D}_s/D_0$	Cortical bone: Endosteal fraction, f_s	Cortical bone: $f_s\overline{D}_s/D_0$
Hip bone		0.6	0.299	0.179		0.0545	0.051	0.0306		0.0093
Scapulae	Hip bone				0.304				0.304	
Clavicles		0.4	0.238	0.095		0.0288	0.072	0.0288		0.0088
Cranium	Cranium	1.0	0.200	0.200	0.140	0.0280	0.272	0.272	0.140	0.0381
Ribs										
Mandible	Ribs	1.0	0.229	0.229	0.134	0.0307	0.136	0.136	0.134	0.0182
Sternum										
Humeri		0.53	0.284	0.150		0.0090	0	0		0
	Femur				0.060				0.060	
Femora		0.47	0.256	0.120		0.0072	0.060	0.0282		0.0017
Vertebrae										
	Lumbar vertebra	1.0	0.258	0.258	0.362	0.0934	0	0	0.362	0
Sacrum										
						TOTAL 0.2516				TOTAL 0.0761

[a] D_0 is the dose rate to a very small tissue-filled cavity. It is usually taken to be 2.7 mrads y^{-1} per pCi $(gCa)^{-1}$.D_s is the mean dose rate to the endosteal tissues on the surface of the trabeculae. Therefore, the dose-rate factor to cells lining bone surfaces due to strontium-90 in trabecular bone is 0.2516 2.7 = 0.68 mrads y^{-1} per pCi $(gCa)^{-1}$ and that from strontium-90 in cortical bone is 0.0761 2.7 = 0.21 mrads y^{-1} per pCi $(gCa)^{-1}$.

TABLE XVI. AIR-DOSE CONVERSION FACTORS FOR A PLANE SOURCE[138]

	^{137}Cs	^{134}Cs	^{106}Ru	^{125}Sb	^{54}Mn	^{95}Zr	^{140}Ba	^{141}Ce	^{103}Ru
Dose-rate conversion factor $K_j B_j$[a] mrad y^{-1} *per mCi* km^{-2}	0.079	0.006	0.032	0.063	0.109	0.358	0.349	0.009	0.073
Mean life T_{mj} years	44.0	1.13	1.44	3.90	1.24	0.257	0.051	0.129	0.157
$K_j B_j T_{mj}$	3.48	0.007	0.05	0.25	0.14	0.09	0.02	0.001	0.011

[a] The conversion factors include dose contributions from daughter nuclides.

TABLE XVII. LATITUDINAL POPULATION AND FALL-OUT DISTRIBUTION[50, 315]

Latitude	Area (Mm^2)	Population (per cent)	Total ^{90}Sr deposition 1964-1967 (mCi km^{-2})	Cumulative ^{90}Sr deposition to 1967 (mCi km^{-2})	Total ^{90}Sr deposition 1966-mid-1968 (mCi km^{-2})
70–80°N	11.6				1.7
60–70°N	18.9	0.4	8.8	26.1	3.5
50–60°N	25.6	11.9	18.9	63.8	4.9
40–50°N	31.5	17.7	20.1	66.6	10.5
30–40°N	36.4	23.4	14.6	42.4	9.2
20–30°N	40.2	25.2	11.1	34.0	7.6
10–20°N	42.8	8.4	8.9	9.1	4.2
0–10°N	44.1	4.0	5.7	4.7	5.6
0–10°S	44.1	4.2	3.5	9.4	3.8
10–20°S	42.8	1.7	2.9	6.4	14.1
20–30°S	40.2	1.5	5.1	8.1	30.7
30–40°S	36.4	1.4	6.2	13.6	19.7
40–50°S	31.5	0.1	7.6	13.6	11.9
50–60°S	25.6				1.8

TABLE XVIII. ESTIMATES OF FACTOR Z

		^{90}Sr 1964-1967	^{90}Sr cumulative to 1967	^{89}Sr 1966-mid-1968
	Mean deposition, $\overline{F}$ (mCi km^{-2})	11.5	42.0	6.3
Northern hemisphere	$\Sigma N_i F_i / \Sigma N_i$	14.3	42.8	7.8
	Z	1.24	1.02	1.24
	Mean deposition, $\overline{F}$ (mCi km^{-2})	4.4	9.0	12.3
Southern hemisphere	$\Sigma N_i F_i / \Sigma N_i$	4.2	9.3	12.9
	Z	0.95	1.04	1.04
	Mean deposition, $\overline{F}$ (mCi km^{-2})	7.9	25.5	9.3
Global	$\Sigma N_i F_i / \Sigma N_i$	13.4	39.8	8.3
	Z	1.69	1.56	0.89

TABLE XIX. DOSE COMMITMENTS FROM NUCLEAR TESTS CARRIED OUT BEFORE 1968

				Dose commitments (mrad)			
				Present estimates			1966 Estimates
Tissue	Source of radiation			North temperate zone	South temperate zone	Whole world	Whole world
Gonads	External	Short-lived		36	8	23	23
		^{137}Cs		36	8	23	25
	Internal	^{137}Cs		21	4	21[a]	15
		^{14}C[b]		13	13	13	13
			TOTAL[c]	110	33	80	76
Cells lining bone surfaces	External	Short-lived		36	8	23	23
		^{137}Cs		36	8	23	25
	Internal	^{90}Sr		130	28	130[a]	156
		^{137}Cs		21	4	21[a]	15
		^{14}C[b]		16	16	16	20
		^{89}Sr		<1	<1	<1	0.3
			TOTAL[c]	240	66	220	240
Bone marrow	External	Short-lived		36	8	23	23
		^{137}Cs		36	8	23	25
	Internal	^{90}Sr		64	14	64[a]	78
		^{137}Cs		21	4	21[a]	15
		^{14}C[b]		13	13	13	13
		^{89}Sr		<1	<1	<1	0.15
			TOTAL[c]	170	51	140	150

[a] The dose commitments to internally deposited ^{90}Sr and ^{137}Cs given for the north temperate zone are considered to represent upper limits of the corresponding dose commitments to the world population.

[b] As in the 1964 and 1966 reports, only the doses accumulated up to year 2000 are given for ^{14}C; at that time, the doses from the other nuclides will have essentially been delivered in full. The total dose commitment to the gonads and bone marrow due to the ^{14}C from tests up to the end of 1967 is about 180 mrads, and that to cells lining bone surfaces is about 230 mrads.

[c] Totals have been rounded off to two significant figures.

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