IONIZING RADIATION: LEVELS AND EFFECTS

A report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, with annexes

VOLUME I: LEVELS

UNITED NATIONS
New York, 1972

NOTE

The report of the Committee without its appendices and annexes appears as *Official Records of the General Assembly, Twenty-seventh Session, Supplement No. 25* (A/8725).

In the text of each annex, Arabic numbers in parenthesis refer to sources listed at the end.

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UNITED NATIONS PUBLICATION
Sales No.: E.72.IX.17

Price: $7.00
(or equivalent in other currencies)

ANNEXES

Levels

Annex A

ENVIRONMENTAL RADIATION

CONTENTS

Introduction

1. Environmental radiation includes cosmic radiation and radiation from nuclides naturally present in the earth's crust, the atmosphere or in waters, as well as radiation from radio-nuclides produced by human activities and introduced into the environment. Individuals are exposed to environmental radiation regardless of health or occupation and the doses received vary widely from place to place and from time to time with respect both to their rate of delivery and to the contribution made by individual sources or type of sources (e.g., natural and man-made).

2. The definition of environmental radiation excludes radiation received by selected individuals for medical reasons or in the course of their occupation, as well as irradiation from a number of miscellaneous sources that expose individuals. The present annex will review environmental sources of radiation both natural (Part One) and man-made (Part Two). Annexes B, C and D will review medical and occupational irradiation and exposure to miscellaneous sources, respectively.

3. The Committee reviewed environmental radiation comprehensively in its 1958, 1962 and 1966 reports (612, 613, 615) and in its 1964 and 1969 reports it

reviewed only man-made radio-activity in the environment (614, 616). In reviewing the latter topic, however, the Committee directed its attention almost exclusively to contamination due to nuclear tests in the atmosphere. With the low rates of injection of nuclear debris now experienced, the importance of this source of contamination has decreased relative to radio-active contamination due to other, rapidly expanding, activities.

4. Hence the Committee has decided to devote considerably greater attention in this report than in previous ones to the contribution that nuclear industry, and the use of nuclear explosions for peaceful purposes, make or may make to radio-active contamination of the environment, and a considerable part of this annex is therefore devoted to reviewing these sources. The reader should be cautioned, however, that the amount of space devoted to discussion of individual sources of environmental radiation does not necessarily reflect their relative importance.

1. *The concepts of average dose*

5. In addition to the radiation doses to *individual* members of the population, that are relevant in assessments of radiation risks, *average* doses are also of interest. Average doses to large populations can be used either to assess the total number of expected injuries in a given population or to compare the risks of two sources of radiation. The latter approach has been used by the Committee in previous reports. Both approaches imply the assumption of a linear, non-threshold relationship between risk and radiation dose.[1] The Committee has stressed that this is a cautious assumption which may or may not be valid.

6. In its evaluation of the environmental contamination caused by nuclear test explosions, the Committee made use of the concept of "dose commitment" as defined in the 1969 report, in order to have a measure of the total future radiation dose to a population caused by the given series of explosions. This concept is described in detail in paragraphs 14-15. Dose commitments may be calculated for different tissues and organs; the Committee has made such calculations for the gonads, the bone marrow and the endosteal cells.

7. The dose commitment is useful in assessing the consequences of any activity per unit practice when significant contributions to the total dose are caused by long-lived nuclides. It is therefore also useful to apply to environmental contamination caused, e.g., by peaceful uses of nuclear explosions and the production of nuclear energy. In these cases the unit practice may be a nominal explosion or one megawatt-year of electrical energy produced, respectively. The concept of dose commitment is particularly useful in the assessment of the trend in a situation before an equilibrium is reached. In such cases the predicted annual dose in a future equilibrium situation is numerically equal to the dose commitment per year of the practice leading to the expected equilibrium.

8. In situations where an equilibrium has already been reached, the actual annual dose (i.e. the dose commitment from each year of practice) is the quantity of immediate interest for assessing the risk to a group of people. This may be taken to be the case with regard to medical and occupational exposures in technologically developed countries. The quantity which is easiest to calculate is then the *per caput* dose, i.e. the average dose within a given population.

9. If the dose distribution over the individual members of the population is not uniform, it may be that a substantial fraction of the *per caput* dose is contributed by the exposure of individuals which, for biological reasons, are not at risk. This would be the case with regard to genetic effects and carcinogenic effects when doses are received by individuals which, because of their child expectancy or life expectancy, respectively, would not be expected to be able to make the possible biological effect manifest.

10. In such cases weighting procedures are appropriate. Weighting for the individual's child expectancy is part of the calculation of the *genetically-significant dose* (GSD), the procedure being described in paragraphs 7-9 of annex B. A weighting for life expectancy could properly have been an element in the derivation of a leukæmia-significant dose although this calculation has not been attempted by the Committee. Instead, the Committee has calculated the population average mean marrow dose without any weighting procedures, this dose therefore being merely a *per caput* mean marrow dose.

11. Weighting procedures are of particular interest when the average dose in a population is composed of contributions from a number of practices each with different weighting factors. The most striking example is the contribution to the genetically-significant dose from a number of different types of diagnostic x-ray examination. Through the appropriate weighting for child expectancy it is possible to assess the relative importance of the different contributions to the GSD, which is of considerable value in planning protection measures.

12. In the case of occupational exposures, the age distribution makes it less important to derive the properly weighted quantities and it will in most cases suffice to make assessments of the *per caput* doses. In this case it is rarely meaningful to assess anything but the *per caput* whole-body dose or the *per caput* gonad dose. In some cases true genetically-significant doses have been reported and seem to be about half the *per caput* gonad dose. Where such assessments have been made they may be considered to give a more representative presentation of the relevant doses.

13. When a whole population is more or less uniformly exposed to radiation from a particular source, the mean dose received from that source, with any appropriate weighting factors for age and sex of those exposed, gives useful information about the relative importance of the exposure. When, however, only part of the population receives exposure from a source, it is important to know the number of people exposed and the doses which they receive from the source. In these circumstances, in order to summarize and to compare the population exposures from different sources it is convenient to express the total exposure from each such source as the product of the number exposed and the dose to which each is exposed, in "man-rads". However, when the term "man-rad" is used in the present report, it is not intended to imply that it is a measure of the total harm from a source, because of the possible influence of factors such as non-linearity of dose re-

[1] This reservation may be unnecessarily stringent in the case of relative risk estimates for dose contributions additional to the natural background radiation, where the *differential* dose increments would be of interest.

sponse, non-uniformity of body radiation, time distribution of the irradiation and radiation quality. With these reservations, the estimate affords a useful comparative indication of the doses delivered to the population, and the quantity may be referred to as the population dose. When based on dose commitment rather than on annual dose, and related to a practice which causes the exposure, it has been used in this report as a measure of the population dose caused by that practice.

2. *Assessment of dose commitments*

14. When a source delivers radiation at a varying rate, as with radio-active material newly released into the environment, it is necessary to integrate over an infinite period of time the average dose rate to individuals that results from the material released during a given and finite time interval. The quantity thus estimated is called the dose commitment from this release. The dose commitment may, alternatively, be referred to the events or series of events or to the practices that have led to the release.

15. More rigorously, if, at time τ, an individual i born at time t_i is exposed to a dose rate $R_i(\tau)$ arising from a certain release, 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. 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

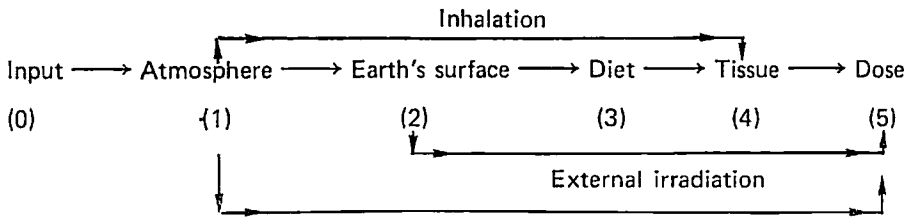
$$D_p(t) = \int_{-\infty}^{t} R(\tau)d\tau, \qquad (3)$$

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. 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 from the release.

16. The calculation of dose commitments is usually fairly simple, particularly when the radiation is external. With internal radiation from nuclides deposited in the body the problem may become highly complex because of the need to predict 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 release of radio-active material 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. Similar schemes could be drawn up for releases into waters or into soil.

17. Since the dose commitment from a given source is the integral over infinite time of the 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 integral of the appropriate quantity 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 environment to the subsequent radiation dose to man. These transfer coefficients must be expressed in terms of the dimensions of the two quantities they link.

18. 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 dose commitment to the tissue is the sum of the contributions of each sequence. For instance,

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

19. Transfer functions and the estimation of their parameters were discussed at length for a number of nuclides in the 1969 report. The essential information from that report will be summarized in this annex whenever necessary.

20. Consistent with the practice of the Committee, radiation doses will, in this annex, be given in rads without regard to their biological effectiveness, but the quality of radiation will be indicated whenever necessary. Rems will be referred to in a few instances when doses have been so reported by the original authors. In these cases the quality factor used by the authors will be mentioned where possible. Population dose rates and population dose commitments will be given in man-rads per year and man-rads, respectively.

I. Cosmic rays

21. The high-energy radiations which enter the earth's atmosphere from outer space are known as primary cosmic rays. When they interact with atomic nuclei present in the earth's atmosphere, secondary particles and electromagnetic radiation are produced and these are called secondary cosmic rays.

A. Primary cosmic rays

22. The origin of the primary cosmic rays is still not yet completely determined. However, it is known that most of the observed radiation originates in our galaxy. Moreover, during periods of solar activity the sun produces solar cosmic rays which consist mostly of non-relativistic protons.

1. *Primary galactic cosmic rays*

23. Primary galactic cosmic rays largely consist of high-energy protons which enter the solar system from interstellar space. Together with protons are ^{4}He ions in the proportion of about 10 per cent. Smaller proportions of heavier particles are also present, together with electrons, photons and neutrinos (15, 197, 504, 639, 640, 643). The approximate charge composition of primary cosmic rays is shown in table 1. The energy spectrum of the primary-cosmic-ray protons has been measured both in and above the earth's atmosphere by means of instruments carried on balloons and spacecrafts (72, 453, 544). Above about 10^3 MeV, the proton flux density decreases exponentially with increasing energy. The energy spectrum is peaked around 300 MeV per particle and is very broad, extending from about 1 to 10^{14} MeV.

24. Below 10^4 MeV, the primary flux density is modified by two processes. In the first place, it is affected by the earth's magnetic field which deflects lower-energy charged particles back into space. This effect is latitude-dependent so that a greater flux of low-energy protons reaches the top of the atmosphere at the poles than in equatorial regions. Thus the ionization produced in the atmosphere is also latitude-dependent. This latitude effect increases with altitude and is illustrated in figure I (453). In the second place

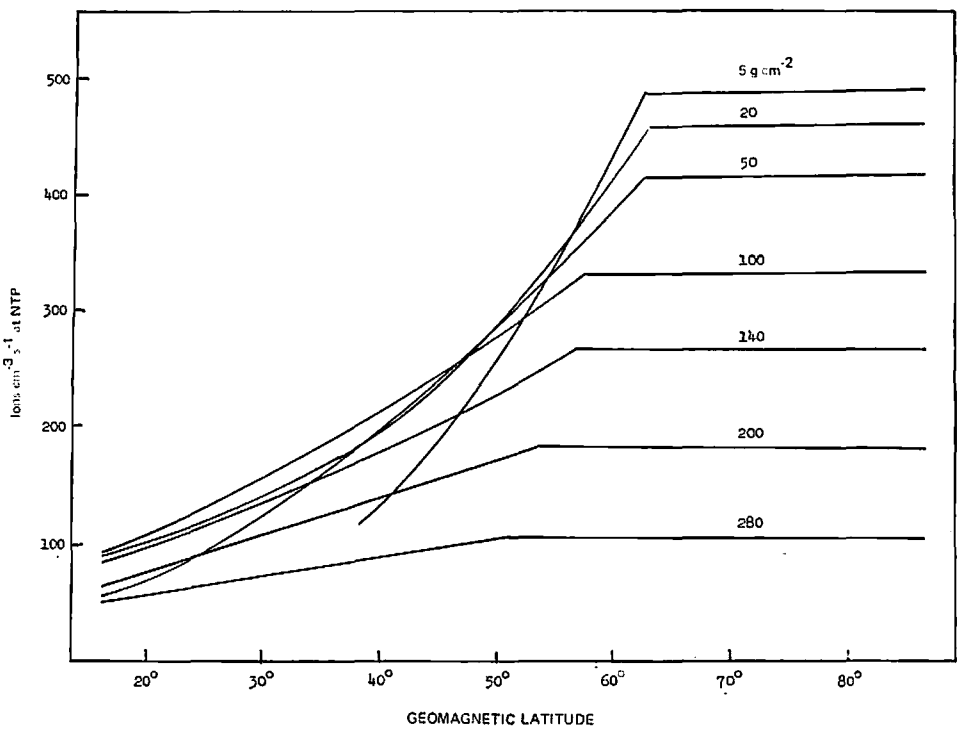


Figure I. Ionization at different latitudes and atmospheric depths (453)

the intensity of the low-energy-proton flux density also varies with the 11-year solar cycle, the density being a minimum during times of maximum solar activity and vice versa; this is known as modulation (453, 455, 456).

2. *Modulation of cosmic rays*

25. The solar-wind theory, originally put forward by Parker (479, 480), adequately accounts for the measured variation of cosmic-ray intensities during the solar cycle. The solar wind consists of an outward flow of plasma, mainly low-energy protons and electrons, travelling out from the sun at several hundred kilometres per second. This wind gives rise to an interplanetary magnetic field which extends out to some 5 10^9 kilometres and this in turn markedly distorts the dipole pattern of the earth's magnetic field (figure II) (183, 458, 459). The solar wind protons have insufficient energy to penetrate the earth's magnetic field and so do not give rise to radiation doses in the atmosphere.

26. During the 11-year solar cycle the magnitude of the solar wind and of the interplanetary magnetic field and its irregularities undergo a cyclical change, reaching a maximum during increased solar activity and a minimum during the period of the quiet sun.

Because the less energetic cosmic-ray particles are deflected away from the solar system by the magnetic irregularities transported by the solar wind, an 11-year modulation of the galactic cosmic-ray flux density at the earth is produced. Moreover, recent measurements made on space vehicles have indeed detected a permanent gradient in the flux density of cosmic rays, the flux density becoming smaller with decreasing distance from the sun (70, 191, 459).

27. Variations in the solar wind due to changes in solar activity over the 27-day cycle cause similar modulations in the galactic cosmic-ray activity. Changes in the ionization and the neutron flux density over an 11-year period are shown in figure III (310, 513).

28. Solar flares are observed as bright flame-like protuberances on the sun's surface which reach maximum brightness in about 10 minutes and then slowly subside. They tend to occur more frequently during periods of sun-spot maximum. Large amounts of energy in the form of visible, ultra-violet and x radiation are emitted

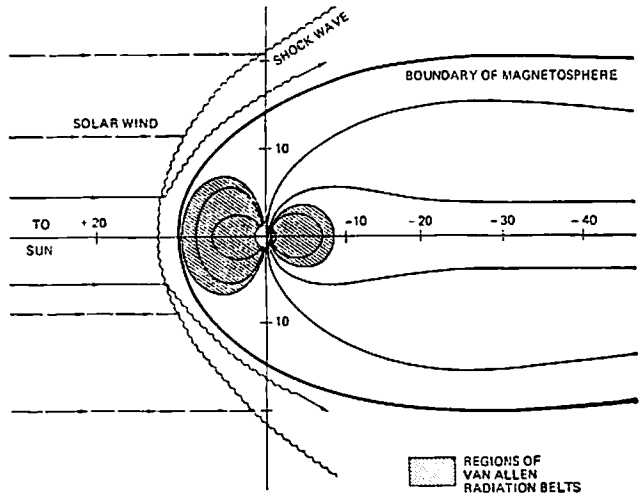


Figure II. Illustration of the intersection of the solar wind with earth's magnetic field (modified from reference 458). The numbers refer to distances in earth radii

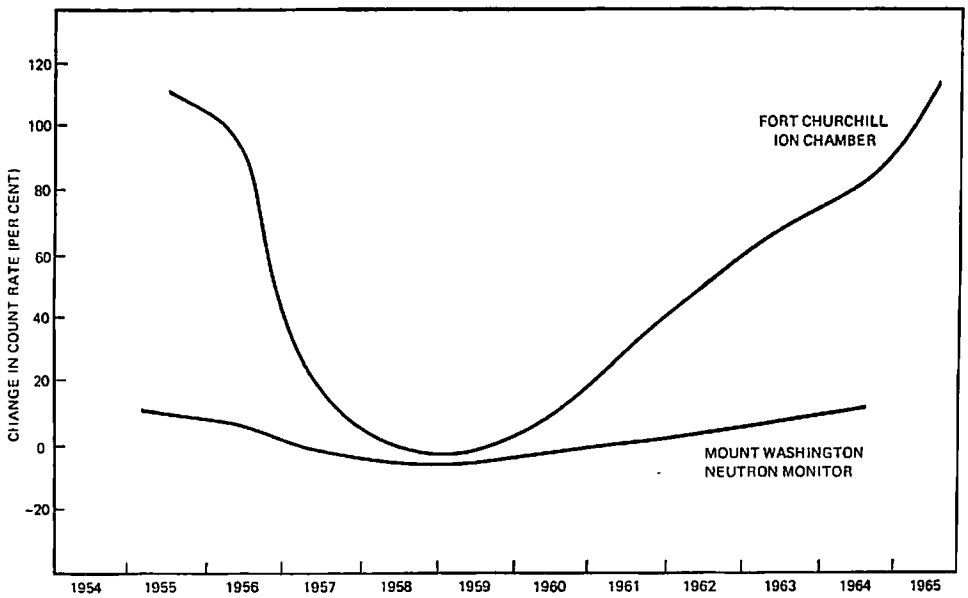


Figure III. Changes in ion and neutron count rates during a solar cycle (310, 513)

and, in the largest flares, large quantities of charged particles, mainly protons and alpha-particles, are also released (544). Measurements indicate that most of the protons have energies in the 1-40 MeV region (72). Because the radiations from solar flares (solar cosmic rays) have relatively low energy, they do not usually cause significant increases in radiation doses at the earth's surface. In fact, only 13 flares produced observable effects in the lower atmosphere between 1942 and 1962 (544). However, large flares can increase the radiation dose rates in the upper atmosphere by a factor of 100 or more for short periods of time.

3. *Radiation belts*

29. There are two so-called radiation belts, often called Van Allen belts, situated between one and eight earth radii above the equator, the inner belt extending from about 30° N to 30° S, the outer belt extending from about 60° N to 60° S (627). Energetic particles, mainly electrons and protons, are trapped in these belts by the earth's magnetic field. They spiral along the lines of magnetic force, being reflected back and forth by the increased convergence of the magnetic field towards polar regions.

30. The belts consist of large numbers of electrons and protons with energies ranging from tens of kilo-electron-volts to hundreds of mega-electron-volts. Although these can present a radiation hazard to astronauts travelling in space, they do not result in any radiation dose to the general population.

B. Secondary cosmic rays

31. When the primary cosmic-ray particles enter the atmosphere, those with higher energy undergo nuclear reactions, while those with lower energy lose energy by ionization. When reacting with nuclei of atoms present in the air they produce neutrons and protons, in addition to pions and kaons (197, 504). Many of the secondary particles have sufficient energy to initiate whole sequences of further nuclear reactions with nitrogen and oxygen nuclei. The initial high-energy reactions are called spallation reactions and quite a

variety of reaction products are formed, some of the more important being ^{3}H, ^{7}Be and ^{10}Be. Three basic types of cascade are produced: the nucleon-nucleon cascade, the nucleon-meson cascade and the photon-electron cascade. The pions rapidly decay into photons or muons. The properties of some of the more important cosmic-ray particles are given in table 2.

32. The nucleonic components, protons and neutrons, are mainly produced in the upper layers of the atmosphere. The protons are formed mainly in spallation reactions, while neutrons are produced both by spallation reactions and by the so-called evaporation of neutrons due to low-energy (p, n) reactions. Neutrons lose energy by elastic collisions and, when thermalized, they are captured by ^{14}N to form ^{14}C. Because nucleons rapidly lose energy through ionization and nuclear collisions, the nucleonic flux density is considerably attenuated in the lower part of the atmosphere and only accounts for a few per cent of the dose rate at sea level.

33. On the other hand, because muons have only a small cross-section for interaction with atomic nuclei, and since they have a mean life of 2.2 microseconds before decay and largely move at relativistic velocities, they penetrate into the lower layers of the atmosphere and are the major cosmic-ray constituent at sea level. The third cascade process, the photon-electron cascade, is initiated from photons produced in the decay of neutral pions. These photons create electron-positron pairs, which in turn produce additional photons by Bremsstrahlung, Compton effect and positron-electron annihilation. Except in the lower layers of the atmosphere, electrons are the main source of ionization (468).

1. *Ionization in the atmosphere*

34. A number of measurements of cosmic-ray ionization at various altitudes have been reported (191, 192, 376, 453, 454, 517, 552). As can be seen from figure I, the ionization in the atmosphere becomes increasingly latitude-dependent with increasing altitude but at high latitudes, between about 60° and 90°, the ionization is almost constant. The ionization also varies with the solar cycle in general, being greatest during the solar minimum and smallest during the solar maximum (453, 454).

35. Ionization measurements in the upper atmosphere between altitudes of 4 and 35 kilometres have been made by Neher (454) over Thule, Greenland (latitude 76° N). These measurements were made annually between 1954 and 1969 and so cover a complete solar cycle. The 1969 measurements agree closely with those of Raft *et al.* (517) made at 54° N latitude in 1969. George (191) has reported ionization measurements made in 1965, during the solar minimum, from a satellite between altitudes of 400 and 1,500 kilometres in polar regions.

36. At sea level, the atmospheric ionization does not vary greatly with latitude or solar cycle. There is a small variation with atmospheric pressure—about 4 per cent per centimetre of mercury (552). Many measurements have been made of sea level cosmic-ray ionization since those reported by Millikan in 1931. The most recent determinations in terms of ion pairs per second per cubic centimetre of NTP air are: Shamos and Liboff (552), 2.18 ± 0.06 at 42° N; Lowder and Beck (376), 2.1 ± 0.1 at 50° N; George (192), 2.6 ± 0.3. The inconsistency of many of the early results has been discussed by Shamos and Liboff (552). Lowder and Beck (376) and also George (191, 192) have compared their measurements with the earlier recorded results. There is some discrepancy between the results of George and those of Lowder and Beck and of Shamos and Liboff. Carmichael (103) has reviewed all the atmospheric ionization measurements and concludes that the results of George are inconsistent with respect to the others. In this annex, a value of 2.14 ions cm^{-3} s^{-1} at NTP is taken as the cosmic-ray ionization in the atmosphere at sea level for computing doses.

2. *Cosmic-ray neutrons in the atmosphere*

37. Most of the dose delivered by low-energy neutrons arises from capture reactions such as (n, γ) and (n, p), while for high-energy neutrons it comes from knock-on protons (443). Since a significant part of the cosmic-ray-neutron spectrum extends from about 0.1 eV to several GeV, some knowledge of its shape is necessary to compute the dose from neutrons.

38. The differential energy spectrum of neutrons at different altitudes and latitudes was computed by Hess *et al.* (243), Lingenfelter (365), Newkirk (462) and by others. The shape and magnitude of the computed spectra agree reasonably well with flux densities that have been reported for different energy ranges (21, 202, 207, 240, 244, 416, 598).

39. More recently, Light *et al.* (361) have computed the neutron spectrum using Monte Carlo methods, obtaining reasonable agreement with spectra measured in the 1-10 MeV energy region. According to these authors, the global average neutron production rate averaged over a solar cycle is 3.9 neutrons cm^{-2} s^{-1}. According to the theory of Hess *et al.* (243), about 20 per cent of these are knock-on neutrons produced by high-energy protons, the remainder being produced by evaporation processes. Figure IV shows the differential energy spectrum of cosmic-ray neutrons at sea level.

C. Doses from cosmic rays

40. For computing dose rates at different altitudes, doses from the ionizing and neutron components will be treated separately. The doses from the ionizing component are obtained from measured ionization in and above the atmosphere. O'Brien and McLaughlin (468) have calculated the ionization produced by the different cosmic-ray components at various altitudes. The energy spectrum they obtain for the vertical components of the proton, muon and pion flux density at sea level agrees well with measured values. The computed total ionization at different altitudes also agrees with measured values to within 30 per cent. The contribution of the different cosmic-ray components to the tissue dose five centimetres inside an isotropically-irradiated phantom as computed by O'Brien and McLaughlin is shown on figure V. These results are very instructive for they show that, below five kilometres, most of the dose arises from muons, with electrons making the next largest contribution. Above 10 kilometres, electrons and protons are the major contributors to dose.

1. *Ionizing component*

41. Assuming that each ion pair in air is equivalent to 33.7 eV, the dose in air per ion pair cm^{-3} s^{-1} is 1.50

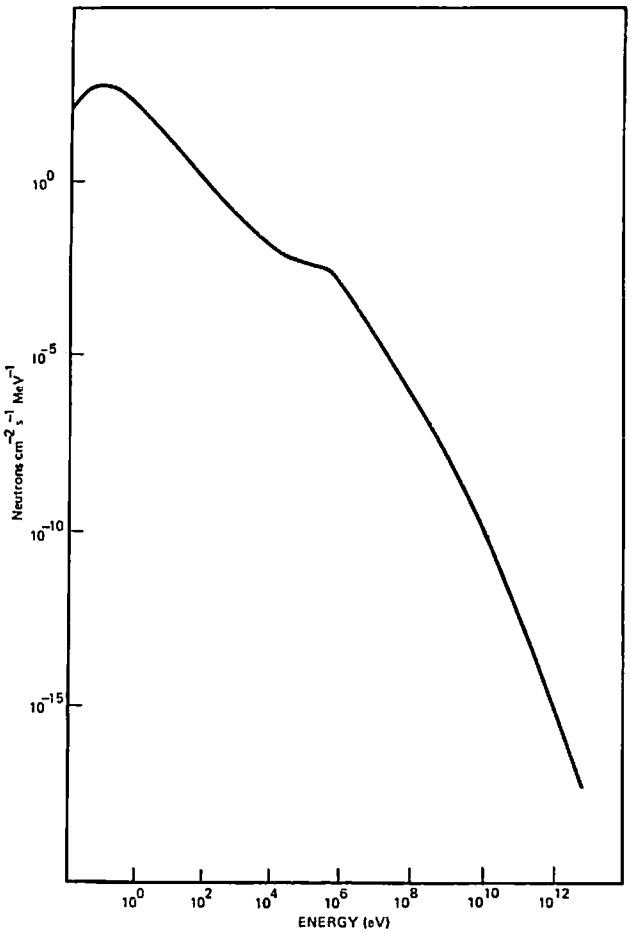


Figure IV. Differential energy spectrum of cosmic-ray neutrons at sea level (219)

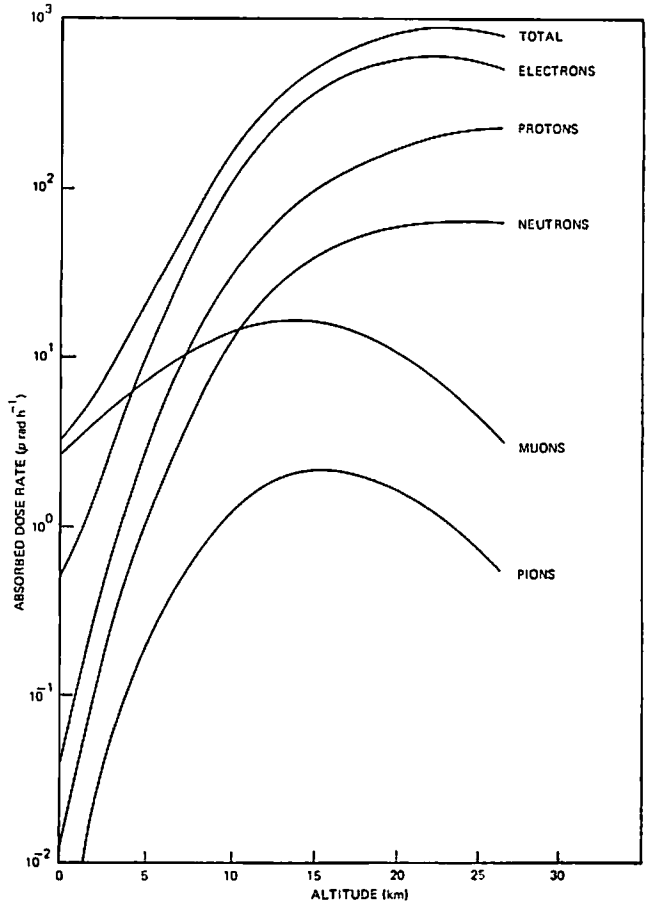


Figure V. Computed dose rate (5 cm inside an isotropically irradiated tissue slab) from the different components of cosmic rays as a function of altitude (468)

μrad h^{-1} (270). The dose rate computed from the measured ionization in the atmosphere for high latitudes is shown in figure VI for altitudes between 1 and 1,000 kilometres. The upper curve for ionization refers to 1965 (solar minimum) and the lower curve to 1969 (solar maximum). Taking the sea level ionization as 2.14 ion pairs cm^{-3} s^{-1} (paragraph 36) the air dose rate is 28 mrad y^{-1}.

2. *Neutron component*

42. In computing the dose from cosmic-ray neutrons care must be taken in the choice of the geometry used for the dose-rate model. Hajnal *et al.* (219) have computed dose-rate factors for the neutron-irradiation of a 30-centimetre tissue slab, using the fluence-to-dose conversion factors published by Irving *et al.* (274) and Neufeld *et al.* (461). This was done for the neutron-energy spectrum shown in figure IV and for the monolateral and bilateral incidence of normal or isotropic neutrons on the tissue slab. Conversion factors for several depths in tissue are shown in table 3.

43. To compute the dose rate at different altitudes, the bilateral incidence of isotropic neutrons on a 30-centimetre slab was assumed and the dose-rate factor was averaged for a cylindrical geometry over a depth range from 0 to 15 centimetres, resulting in 4.93 μrad h^{-1} with a flux density of 1 neutron cm^{-2} s^{-1}. This factor is much the same as that for the dose rate at a depth of 5 centimetres in a 30-centimetre slab.

44. The measured neutron flux densities of Boella *et al.* (65), Greenhill *et al.* (207), Haymes (240) and Jenkins *et al.* (294) were used to compute the neutron dose. Where necessary, this was done by taking into account the shape of the differential-energy spectrum of figure IV. The data were also normalized to high latitude and to solar maximum or minimum (454, 554). The resulting neutron dose rates are shown in figure VI. The dose rate reaches a maximum value of 30 μrad h^{-1} at 20 kilometres during solar minimum. During solar maximum, the dose rate at 20 kilometres is reduced by a factor of two. Extrapolating the neutron dose-rate curve of figure VI to zero altitude gives an estimate of the sea-level dose rate of about 0.48 mrad y^{-1}.

45. A number of measurements of the neutron flux density at sea level have been reported. Some of these results are shown in table 4, together with the corresponding dose rate. At sea level, the flux density is quite small and difficult to measure accurately. Kastner *et al.* (314) found that the flux density was different over water and dry land. In addition, they also found a considerable build-up in the low-energy-neutron flux density due to the moderating influence of water in the soil and the absence of nitrogen, which acts as a sink for thermal neutrons. The most recent flux density measurements, those of Hajnal *et al.* (219), compare well with those of Boella *et al.* (65), Kent (325) and Yamashita (659) and with the computed values of O'Brien (467). A quality factor of 6 is assigned to

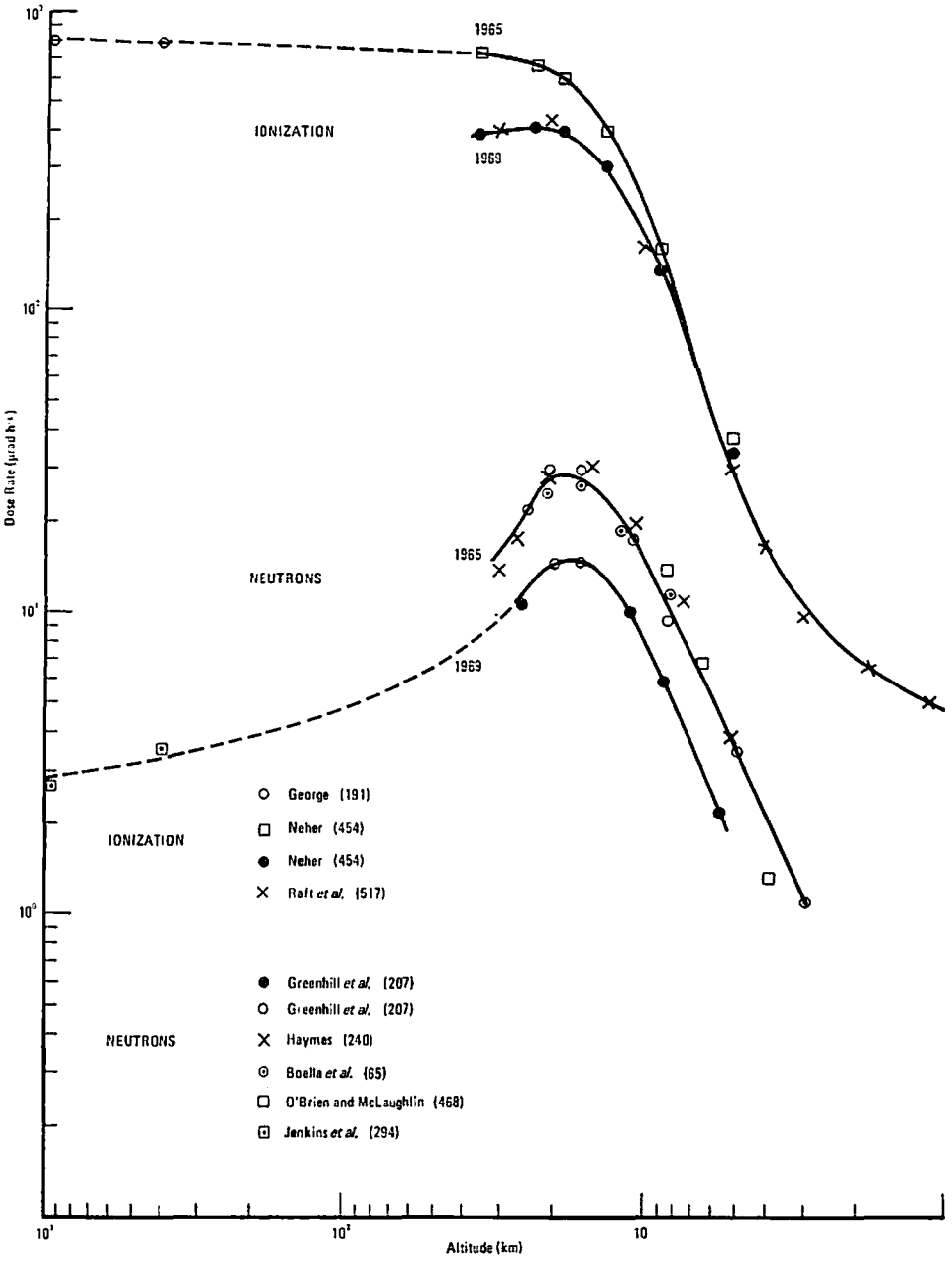


Figure VI. Absorbed dose rates from the ionizing and neutron components of cosmic rays at different altitudes for 1969 (solar maximum) and 1965 (solar minimum)

this radiation, based upon the dose-equivalent and absorbed doses computed by Hajnal *et al.* (219) for isotropic bilateral incidence on a slab averaged to a depth of 15 centimetres.

46. A value of 0.35 mrad y^{-1} is adopted for the average tissue absorbed dose rate from neutrons at sea level at 40° latitude, but it must be borne in mind that there may be considerable variation due to the effects discussed above. Using the vertical cut-off rigidity data of Shea and Smart (554), the sea-level absorbed dose rate in polar regions is 0.35 mrad y^{-1}, and 0.2 mrad y^{-1} in equatorial regions. In making the present estimates of dose rates from neutrons, no account is taken of attenuation or build-up due to shielding by surrounding structures.

3. *Doses to persons in supersonic transport aircraft*

47. The prospect of the development of a supersonic aircraft transport (SST) system on a large scale during the next decade poses the question of the cosmic ray dose rates to which passengers and crews will be exposed and of the contribution of this to the average doses received by the world's population. The first generation of supersonic aircraft will fly at altitudes which may range up to 20 kilometres compared with 12 kilometres for standard jet aircraft. The doses will of course depend markedly on the altitude and latitude of the flight operations. Judging by the ionization densities shown in figure I, the dose rates delivered to persons at these altitudes will be much greater at latitudes higher than 50°.

48. When considering dose rates received by persons exposed at such high altitudes, it is necessary to discuss separately two contributions. In the first place are the background galactic cosmic rays, ever present, which vary in intensity by a factor of about two during the sun's 11-year solar cycle. Secondly, there may occasionally be large short-term increases in the radiation as a result of intense fluxes of solar protons originating from solar flares.

49. Estimates of the dose rates from both the ionizing and the neutron components of galactic cosmic rays at high latitude and at altitudes of 12 and 20 kilometres can be obtained from figure VI. These results for solar minimum are shown in table 5. It should be noted that neutron dose rates determined from whole-body ^{24}Na burdens, compared with dose rates determined from surface monitors, indicate a considerable build-up in neutron flux density inside the human body (80, 546).

50. In order to determine dose rates at altitudes at which an SST might fly, Fuller and Clarke (185) made measurements from balloons at 20 kilometres over Fort Churchill, Canada, in July 1964, near solar minimum. Their measurements indicated a dose rate from the ionizing component of 750 μrad h^{-1}. An average quality factor of 1.5 was established for this ionizing component from a study of tracks recorded in nuclear emulsion plates. The neutron rem counter indicated a dose-equivalent rate from neutrons of 500 μrem h^{-1}. O'Brien and McLaughlin (469) concluded that this neutron dose-equivalent measurement corresponded to a surface dose in a phantom irradiated isotropically from above. Since the dose-equivalent rates per neutron cm^{-2} s^{-1} for monolateral isotropic incidence on a slab surface and for bilateral isotropic incidence averaged through 15 centimetres are, from table 3, 68 and 29 μrem h^{-1}, respectively, the 500 μrem h^{-1} of Fuller and Clarke reduces to 210 μrem h^{-1} for bilateral isotropic incidence averaged through 15 centimetres. With a quality factor of 6, this corresponds to 35 μrad h^{-1}, in reasonable agreement with figure VI.

51. Fuller and Clarke calculated the absorbed dose rate from nuclear stars recorded in the nuclear emulsion plates as 64 μrad h^{-1}, with an average quality factor of 8.5. Because of the high quality factor, the dose rate resulting from stars is quite significant and has been included in table 5. The authors were not certain whether all or part of the dose rate from nuclear stars was recorded in the ionization chamber measurements or not. At the most, failure to subtract the contribution of stars from the ionizing component would overestimate the absorbed dose by 10 per cent. Using the maximum estimates for the absorbed dose rates shown in table 5 and assuming a quality factor of 1.0 for solar radiation, the total dose-equivalent rate at 20 kilometres altitude and at high latitude is 1,700 μrem h^{-1}.

52. The average dose rates from solar particles are listed in the last column of table 5 (267). These estimates were made by the ICRP working group by averaging the effects of solar flares over the period 1952-1960. It can be seen that at these altitudes the average contribution from this source is small compared with that from galactic cosmic rays. Although radiation of solar origin does not contribute significantly to the average dose rate, during an occasional intense solar flare radiation levels at these altitudes may increase by several orders of magnitude. For example, during the giant solar flare of 23 February 1956, dose rates at 20 kilometres and at high latitude have been estimated to be as high as 0.2-0.6 rad h^{-1} (267). For this reason SST aircraft will carry radiation warning devices enabling the pilots to take evasive action by bringing the aircraft to lower altitudes when the dose rate reaches a prescribed action level. These giant solar flare events only last for about 10 hours and occur a few times in each solar cycle, and therefore are not likely to add significantly to the total dose burden.

53. The air speed of SST aircraft will be in the range 2,300-2,900 km h^{-1} compared with 800 km h^{-1} for conventional jets. A flight from Europe to North America will therefore take some two to three hours instead of the present eight hours. In a conventional jet aircraft cruising at an altitude of 12 kilometres the dose-equivalent rate is 600 μrem h^{-1} or 0.7 μrem km^{-1}. In a supersonic aircraft cruising at an altitude of 20 kilometres, the dose-equivalent rate is 1,700 μrem h^{-1}, which also corresponds approximately to 0.7 μrem km^{-1}.

54. Using the dose rates of cosmic rays given in table 5, the dose for an Atlantic crossing will be about 2 millirads in an SST compared with about 2.6 millirads for present-day jets. The latter figure does not include the dose contribution from nuclear stars. Thus we see, as was noted by Schaefer (546), that the doses per passenger-kilometre will not be very different in SST aircraft than they are at present and may be lower. However, the doses received by the crew of SST aircraft will depend on the number of hours flown and on the flight altitude and latitude, and may range up to a dose equivalent of 1 rem y^{-1}. For the crews of conventional jet aircraft, flying 600 hours per year, the dose-equivalent rate is about 0.5 rem per year.

55. During 1970, some 4.6 10^{11} passenger-kilometres were flown at an average speed of 580 km h^{-1}, throughout the world excluding China (265). An upper limit to the dose received from cosmic galactic radiation is 2.5 10^5 man-rads which corresponds to an average world population dose rate of about 0.1 millirad per year per person.

56. Schaefer (546) has investigated the contribution to doses at SST altitudes of the heavy-nuclei components of cosmic rays. These particles have a high LET and give rise to a so-called "micro-beam" irradiation. It was concluded that the "micro-beam" part of the heavy flux was virtually extinguished at SST altitudes.

II. Terrestrial radiation

A. Internal irradiation

57. Radio-active nuclides occurring in our natural environment enter the human body mainly through food and water, inhalation being of secondary importance, except for radon daughters. The dose rates to particular body organs are ideally derived from measured tissue concentrations, although an indirect estimation of the dose rates can be made from studies of the distribution of the radio-nuclides in the environment and in diet and from knowledge of their metabolic behaviour. Owing to the varying content of natural radio-active nuclides in the environment and in diet, the levels of radio-active intake, and therefore the corresponding concentrations in the human body, may vary from place to place for elements not subject

to haemostasis. In a given location, time variations also occur as a result of changes in diet. Because of limited geographical representation and of the obvious limitations of sampling, the arithmetic means calculated from the most frequent values will be accepted in this annex, although they may not be strictly representative for the whole world population.

58. The natural radio-active nuclides have been classified into those that are being continually produced by the interactions of cosmic-ray particles with matter, and those that were originally present at the formation of the earth, with their decay products.

1. *Cosmic-ray-produced radio-active nuclides*

59. A total of twenty radio-nuclides, produced by cosmic rays in the earth's atmosphere, have been detected (table 6). From the point of view of radiation doses, only ^{14}C and, to a lesser extent, ^{3}H are worth considering.

(a) *Tritium*

60. Tritium occurs naturally in the surface waters of the earth, being produced in the atmosphere by the interaction of high-energy cosmic rays with atmospheric nitrogen and oxygen (paragraph 31). Recently, its production rate, measured directly (604), has been found to be 0.20 ± 0.05 tritons cm^{-2} s^{-1}. This figure corresponds to an annual production rate of 1.6 MCi y^{-1} and to a steady-state inventory in the biosphere of 28 megacuries. Since 1954 large amounts of man-made tritium have been released into the environment from nuclear explosions, most of it arising from tritium unused in the thermonuclear reaction. Discharges from the nuclear power industry also contribute to the inventory of tritium. Finally, tritium is widely used as a radio-active luminizing material in products available to the general public such as watches and clocks. Those sources of "artificial" tritium will be discussed later in this annex and in annex D.

61. Prior to its injection into the biosphere from nuclear tests, levels of tritium in waters of the mid-latitude regions of the earth were in the range 6-24 pCi l^{-1} (316, 637). About 90 per cent of natural tritium resides in the hydrosphere, 10 per cent in the stratosphere and only 0.1 per cent in the troposphere (41). The low inventory of tritium in the troposphere is due to the fact that tritium in the form of HTO is rapidly washed out by rain. Early estimates of the half-residence time were 21 to 40 days (42, 359), but more recent work has shown that it is only 10 days (339).

62. The dose rates resulting from natural tritium have been calculated with the assumption that the tritium-hydrogen ratio in the body is essentially the same as that in the surface waters. With an average beta-particle energy of 5.69 keV, the dose rate from natural tritium to soft tissue would be in the range 0.6-2.5 μrad y^{-1}.

(b) *Carbon-14*

63. Carbon is one of the elements that are essential to all forms of life and thus is involved in most biological and geochemical processes on earth. Associated with the stable isotopes (98.9 per cent ^{12}C and 1.1 per cent ^{13}C), there is always a very small but variable amount of ^{14}C, a pure beta-emitting ($\bar{E} = 50$ keV) radio-active isotope of carbon with a half-life of 5730 ± 30 years.

64. Natural ^{14}C is produced in the upper atmosphere by interaction of cosmic-ray neutrons with nitrogen, according to the reaction ^{14}N (n, p) ^{14}C. Its production rate is not accurately known, the most recent calculated averages over a solar cycle being 2.5 ± 0.5 atoms s^{-1} cm^{-2} (365) and 1.98 atoms s^{-1} cm^{-2} (361). A production rate of 2 atoms s^{-1} cm^{-2} corresponds to 0.03 MCi y^{-1} and to a steady-state inventory of 280 MCi. The contribution of ^{14}C added to the atmosphere by nuclear and thermonuclear tests will be discussed in paragraphs 167-169.

65. Carbon-14 is present in atmospheric carbon dioxide, in the terrestrial biosphere, and in the bicarbonates dissolved in the ocean. The specific activity of natural radio-carbon in the terrestrial biosphere, as measured in wood grown in the nineteenth century, was 6.13 ± 0.03 pCi $(gC)^{-1}$ but, during the recent decades, it has experienced a slight decrease caused by the artificial combustion of ^{14}C-free fossil fuel (589). The reduction in the specific activity of atmospheric ^{14}C in the absence of nuclear tests has been theoretically estimated at —3.2 per cent in 1950, —5.9 per cent in 1969, and —23 per cent in 2000 (34).

66. The decay rate of natural ^{14}C is equal to the average specific radio-carbon activity before the advent of nuclear tests times the average number of grams of carbon present per square centimetre of the earth's surface. Estimation of those quantities in the different reservoirs of ^{14}C yields a decay rate of 1.81 disintegrations s^{-1} cm^{-2} (589). This is less than the production rate but considering the uncertainties in total carbon mass estimates, this is a good agreement. It has been suggested, however, that the present-day inventory does not correspond to the equilibrium value, but is increasing (348, 589). In fact, measurements of wood samples of known age show that variations of atmospheric ^{14}C, amounting to a few per cent, have occurred in the past 6,000 years. Two types of variations have been recognized: one, with a time scale of the order of 100 years, has been explained by the solar wind modulation of the cosmic-ray flux density (589); the other, with a time constant of more than 1,000 years, may largely be due to a variation of the geomagnetic shielding of the earth (208).

67. Assuming that 6.1 pCi $(gC)^{-1}$ is the specific activity of natural ^{14}C in the terrestrial biosphere, 50 keV the average beta energy, and 18 per cent the average carbon content of the whole body, then the average dose throughout the human body is 1.02 mrad y^{-1}. The highest dose is delivered to fat. In soft tissues, the annual dose rate is 0.68 mrad y^{-1} if the carbon content is taken as 12 per cent (613). In bone, the reported values of the carbon content are 13 per cent (266), and 15.5 per cent (577). The average of the two values leads to a dose rate of 0.81 mrad y^{-1} to endosteal tissues. Owing to the Suess effect, the dose reduction was approximately 0.04 mrad y^{-1} in 1969.

2. *Primordial radio-active nuclides*

68. The primordial radio-nuclides can be divided into those which decay directly to a stable nuclide (table 7), and those belonging to the three radio-active series, headed by ^{238}U, ^{235}U, and ^{232}Th (figure VII). The only non-series radio-nuclides of significance are ^{40}K and ^{87}Rb, which have similar chemical properties.

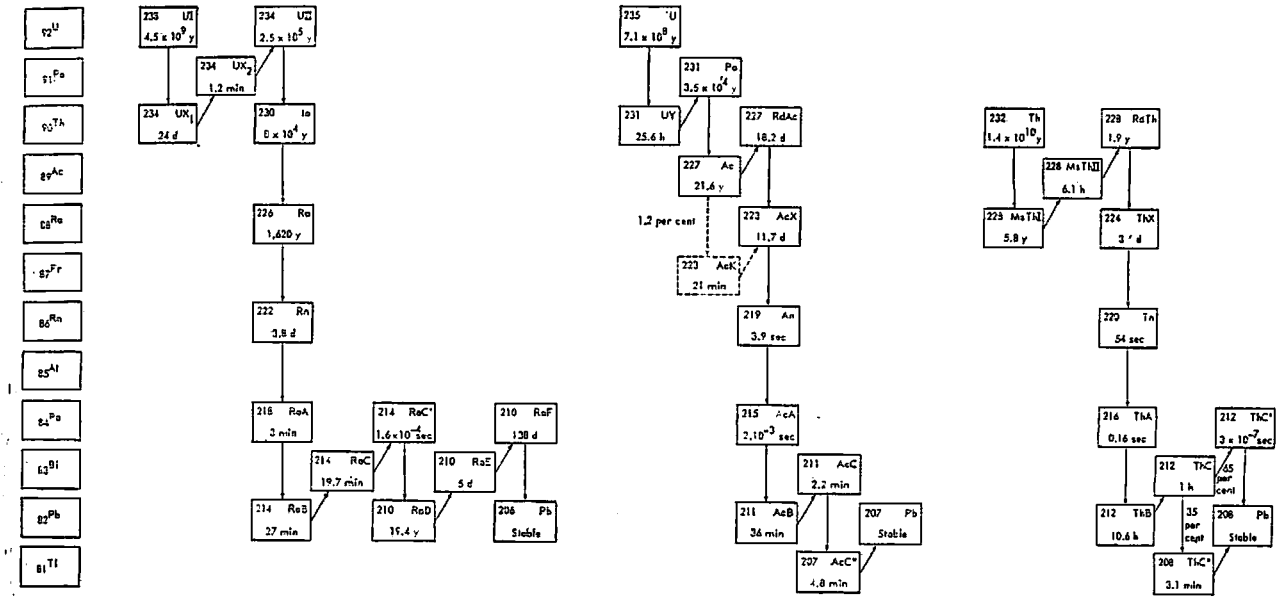


Figure VII. Decay schemes of the natural series[a] (boxes show mass number, historical name and half-life)

[a] Parallel decay branches of less than 1 per cent are not included

(a) *Potassium-40*

69. Potassium-40 is the main naturally-occurring source of internal radiation, despite its low isotopic ratio of 0.0118 per cent (40). The activity of ^{40}K in soils is on the average an order of magnitude higher than that of ^{238}U and ^{232}Th. In sea-water, ^{40}K constitutes the bulk of the activity with a concentration of about 300 pCi l^{-1} (237).

70. Potassium enters the body mainly in food-stuffs and is under close homeostatic control. Variations in the composition of diet thus have little effect on the radiation dose received, so that knowledge of the behaviour of potassium in food chains is of no practical assistance in the assessment of man's exposure to radiation (540). The potassium content in the body varies considerably from one organ or tissue to another. Some tissues such as muscle, brain, and blood cells contain about 0.3 per cent potassium, blood serum has a normal level of 0.01 per cent and fat contains none (266, 577). In bone, a representative value may be taken as 0.05 per cent by weight for wet bone without marrow (577).

71. The average potassium content of the whole body as a percentage of body weight depends upon body build and is smaller in obese persons. Using whole-body counting techniques, potassium levels as a function of age have been investigated (44) for large populations (figure VIII). Recent results are consistent with those given by the Committee in its 1962 report for individuals of 20 years of age or older, but are up to 15 per cent lower for younger ages.

72. On the basis of a mean potassium content in tissues of 0.2 per cent, the dose rate to the soft tissues can be calculated as 19 mrad y^{-1}, the beta and the gamma doses amounting to 17 and 2 mrad y^{-1}, respectively (577). In bone, the potassium content being about one quarter of that in soft tissues, the annual dose to the osteocytes or to the tissues in the Haversian canals is about 6 mrad y^{-1}. In the active marrow, the potassium content is about 0.2 per cent which leads to an estimated dose rate to the bone marrow and to the cells near the endosteal surfaces in the trabecular cavities of 15 mrad y^{-1} (577).

(b) *Rubidium-87*

73. The isotopic abundance of ^{87}Rb, which is a pure beta emitter, is 27.85 per cent. The average concentration of rubidium in the whole body is 17 ppm; in bone, ovaries and testes, the corresponding figures are 10, 4.5 and 12 micrograms per gram of wet tissue, respectively (577). The dose rates to the gonads and to the bone tissues, resulting from decay of ^{87}Rb in the body, have been estimated from these concentrations (table 8). The average gonadal dose rate would

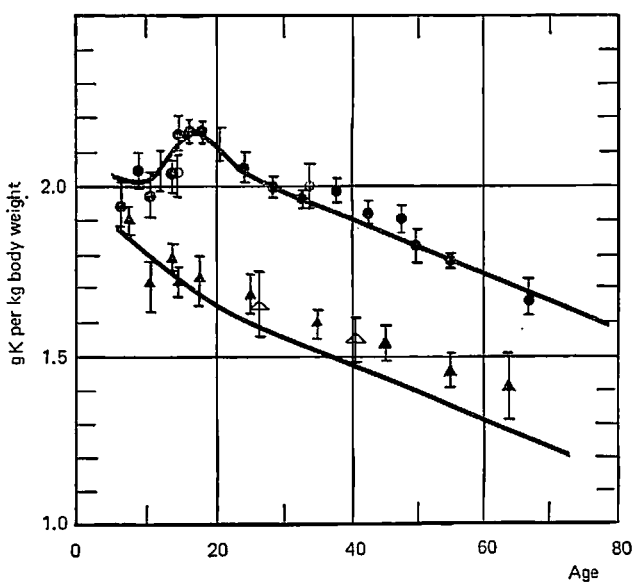


Figure VIII. Potassium concentration in the human body. The upper curve and circles refer to men, the lower curve and triangles to women. The curves represent the results of 10,000 measurements (466), the solid circles and triangles 802 determinations (16) while the open circles and triangles are the results of measurements performed on 57 subjects (44)

be about 0.3 mrad y^{-1} while the dose rate to the small tissue inclusions within bone would be approximately 0.4 mrad y^{-1}. Assuming that the concentration of rubidium in the active marrow is the same as that averaged over the whole body, the dose rate to the bone marrow and to the cells near the endosteal surfaces in the trabecular cavities would be 0.6 mrad y^{-1}.

(c) *Uranium and thorium series*

74. Uranium and thorium are widely distributed throughout the earth's crust where they present on the average the same activity concentration (225). The radio-active decay chains of ^{238}U and ^{232}Th are presented in figure VII. Uranium and radium enter the biosphere through the soil into plants, and then in herbivorous animals and in man. Further down the chain, radon, as a gas, escapes to a certain extent from the soil into the atmosphere and decays into isotopes of solid elements which are important contributors to radio-activity in the environment.

75. Thus, the ^{238}U series has been classified in four separate sub-series in which the activity of the parent controls to a large degree the activity of the decay products: (*a*) the isotopes ^{238}U and ^{234}U which can be considered to be in radio-active equilibrium in the environment as they are separated by two much shorter-lived nuclides, ^{234}Th and ^{234}Pa. At high concentrations, these isotopes of uranium present a chemical toxicity problem rather than a radiological hazard (540); (*b*) ^{226}Ra, as its concentrations in diet and man are not clearly related to those of its long-lived precursor and as the environmental pathways of its decay product, an isotope of a noble gas, are evidently not the same as those of a solid; (*c*) ^{222}Rn and its short-lived daughters (through ^{214}Po) of significance for inhalation; and (*d*) the long-lived ^{222}Rn decay products (^{210}Pb, ^{210}Bi, and ^{210}Po) which enter plants mainly by atmospheric deposition.

76. The ^{232}Th series is constituted by different isotopes of the same elements and may be treated in the same way as that of ^{238}U. ^{232}Th will be considered by itself as its decay product is an isotope of radium (^{228}Ra) of sufficiently long half-life to warrant an independent study. ^{228}Ra is the precursor of a sub-series which ends with ^{224}Ra. The gaseous element of the chain is ^{220}Rn, with short-lived daughters. ^{220}Rn does not have any long-lived decay product, as opposed to ^{222}Rn.

77. The decay chain of ^{235}U, also presented in figure VII, will not be dealt with here because the $^{235}U/^{238}U$ activity ratio in nature is less than 5 per cent.[2] Moreover, the very short half-life of ^{219}Rn, the gaseous element in the chain, leads to an atmospheric activity of its decay products which is about 2,000 times less than that of ^{222}Rn (104).

(i) *Uranium*

a. *Concentrations in the environment*

78. *Soil.* The typical content of ^{238}U in the accessible lithosphere has been estimated by the Committee in 1966 to be about 2.8 ppm. In general, igneous rocks and granites contain higher concentrations of uranium than sedimentary rocks such as limestone and chalk. However, some sedimentary rocks of marine origin contain very high concentrations of uranium (540).

79. *Air and water.* Uranium is present in the air in minute quantities. The natural debris may be mixed with man-made aerosols such as dust from building materials or smoke from both industrial and domestic sources (222). The concentrations observed in city air range from less than 10 to 1,500 pg m^{-3} (222, 411, 645). In sea water, the uranium concentration is quite uniform (from 2 to 3.7 $\mu g\ l^{-1}$), the low values being associated with near-coastal waters (55, 550, 576). On the other hand, concentrations in fresh waters show a high variability, with reported levels ranging from 0.024 to 200 $\mu g\ l^{-1}$ (433, 525, 645).

b. *Intake, levels and doses in man*

80. There is very little information concerning the concentrations of uranium in man and in his diet. Values of daily intake of about 1 $\mu g\ d^{-1}$ seem to be typical in the United Kingdom (224), the United States (645), the USSR (670) and France (550) while it reaches 30 $\mu g\ d^{-1}$ in one area of the Soviet Union (683). In man, the range of concentrations has been found to be 0.1-0.9 nanogramme per gramme of wet soft tissue, to be compared with 20-30 nanogrammes per gramme of bone ash (224, 645). The corresponding dose rates to bone, calculated by the method of Spiers (577), are small (table 9); in the calculations, uranium was assumed to be uniformly distributed in mineral bone, although that may not be the case (223, 536). The total mass of mineral bone in man has been taken to be 5,000 grammes corresponding to 1,000 grammes of calcium (see paragraph 205). Bone has been assumed to yield 2.7 grammes of ash per gramme of calcium.

(ii) *Thorium-232*

81. Like uranium, thorium is more abundant in acidic than in basic rocks. It constitutes up to 10 per cent of monazite, which is particularly abundant in certain areas of Brazil and India. Experiments in which plants have been grown in solutions containing thorium show that it is readily adsorbed on roots, largely by physico-chemical processes (492), but that the concentration in shoots is negligible compared to that of radium (147). In the oceans, a very small amount of thorium is found suspended; the thorium-to-uranium concentration ratio is only 2 10^{-5} or less (315).

82. No information on the intake of ^{232}Th has been found in the literature. Measured levels in rib bone (379) show a linear increase with age. The average value for an adult population would be about one femtocurie[3] per gramme of ash, which is about an order of magnitude less than the levels obtained for uranium.

(iii) *Radium*

a. *Concentrations in the environment*

83. *Soil.* Radium isotopes are normally present in any type of soil at varying levels of radio-active equilibrium with their parents. Since, on the average, ^{232}Th and ^{238}U have about the same activity concentration (237) the same can be said for ^{226}Ra and ^{228}Ra, the two isotopes under consideration. The normal content of ^{226}Ra may be slightly increased by the use of phosphate fertilizers (418). The uptake of radium by plant shoots is much higher than that of thorium, lead or polonium (147), but is low in comparison to cal-

[2] One gramme of uranium contains 0.33 μCi of ^{238}U, assumed to be in equilibrium with ^{234}U, and 0.015 μCi of ^{235}U.

[3] One femtocurie (fCi) equals 10^{-15} curie.

cium (328). An exception to that rule is constituted by the Brazil-nut tree (*Bertholletia excelsa*) which accumulates radium, along with barium, preferentially to calcium in some tissues of the fruit (494, 540), although the soil on which it has been observed to grow does not have an elevated content of radium.

84. *Air.* The natural background concentration is constituted by the airborne particulate matter picked up from the earth. In city air (222), it can be estimated at around seven attocuries[4] per cubic metre, if it is assumed that uranium and radium have the same activity in the atmosphere. Fossil-fuelled power plants release very small amounts of radium, which may be detectable in the air around those installations (404). The maximum activity of ^{226}Ra dispersed each year by the combustion of coal has been estimated at 150 curies (291).

85. *Ocean water.* In ocean surface water, the ^{226}Ra content is low and relatively constant, with a value of about 0.05 pCi l^{-1} (83, 597). It is primarily supplied by diffusion from ^{230}Th-bearing deep-sea sediments (83). Similarly, ^{228}Ra diffuses from ^{232}Th sediments and is relatively abundant in waters in contact with terrigenous sediments (434) but even there it is in a lower concentration than ^{226}Ra.

86. *Fresh water.* In fresh waters, the ^{226}Ra content is highly variable, typical figures ranging from 0.01 to 1 pCi l^{-1} (26, 139, 433). The highest concentrations, ranging up to 100 pCi l^{-1}, are found in mineral waters (139, 245, 508). Those drinking-water supplies drawn from surface waters do not in general contain significant amounts of radium. Flocculation and water-softening processes remove the bulk of the radium activity from water.

b. *Transfer to man*

i. *Areas of normal external-radiation background*

87. The average daily intake of ^{226}Ra in areas of normal radiation background has been found to be about 1 pCi $(gCa)^{-1}$ in the United States, in the United Kingdom, in Argentina, in India, in the USSR, and in France (table 10). In the Soviet Union, a study conducted in one of the cities of Central Asia showed a high ^{226}Ra intake of 17 pCi $(gCa)^{-1}$ explained partly by unusually high levels of ^{226}Ra in water and in bread (676). Individual intakes are increased when food items which have high concentration factors are consumed; levels of ^{226}Ra and ^{228}Ra in Brazil nuts may reach several thousands of picocuries per kilogramme (494) while Pacific salmon, which is eaten in large quantities by Eskimos and North American Indians, contain about 20 pCi kg^{-1} of ^{226}Ra (293). The ^{228}Ra daily intake is not well known but the few existing measurements (table 10) seem to indicate that it is more than half of that of ^{226}Ra.

88. About 80-85 per cent of radium is contained in the skeleton, the remaining fraction being distributed approximately uniformly in soft tissues. World-wide variations in ^{226}Ra skeletal burdens in areas of normal rate of intake are not large and show a spread between 4 and 40 fCi $(g\ ash)^{-1}$ in different localities (table 11) with an arithmetic average of 14 fCi $(g\ ash)^{-1}$ or about 40 picocuries per skeleton. The average ratio between activities of ^{228}Th and ^{226}Ra in bone ash was found to vary between 0.25 and 0.5 (256, 380, 582) which, assuming radio-active equilibrium between ^{228}Ra and ^{228}Th in bone, leads to an estimated upper limit of skeletal burden of 20 picocuries of ^{228}Ra in normal areas.

ii. *Areas of high external-radiation background*

89. People living on food-stuffs grown in areas of high natural radio-activity have daily intakes well above normal values but indications on their body burdens are very limited. The Indian population along the Kerala coast, including the monazite-bearing high-radiation belt, has an estimated *per caput* intake of ^{228}Ra of 162 pCi d^{-1} (424); the corresponding figure for ^{226}Ra is only 2.85 pCi d^{-1} (110). The analysis of a femur bone yielded a ^{226}Ra concentration of 143 fCi $(g\ ash)^{-1}$.

90. In Brazil, a survey in the Araxa-Tapira region (495) showed that, out of a population of 1,670 people living in or around the radio-active anomalies of Barreiro and Tapira, only 196 individuals are ingesting alpha emitters at a level five times or more than that of a similar group living in Rio de Janeiro. Their intake of radium ranged from 60 to 240 pCi d^{-1} of ^{228}Ra and 10 to 40 pCi d^{-1} of ^{226}Ra. The mean concentration of ^{226}Ra in ashed teeth of the population living in that area is 85 fCi g^{-1} (496); as the level of ^{226}Ra in teeth is approximately equal to that in bone (375), the result leads to an estimated skeletal burden of 230 picocuries.

91. In Guarapari, body burdens of ^{208}Tl, a decay product of ^{228}Ra, are of the order of 10 nanocuries (132). Since the levels in food are normal and the ^{220}Rn concentrations in breath are elevated, this high burden probably results from inhalation of fine dust particles containing the precursors of ^{220}Rn.

c. *Dose rates*

92. The fraction of radon retained by the various organs of the body after decay of radium has to be taken into account when computing the doses. The half-life of ^{220}Rn is sufficiently short so that most of it decays where it is produced; however, some is detectable in the breath. In the case of ^{222}Rn, the Committee adopted, in its 1966 report, an average skeleton retention factor of 0.33, but it has been shown that this factor is not constant at all sites (507). In soft tissues, a conservative assumption is that the ^{222}Rn retention is the same as in bone (577). The annual alpha doses from ^{226}Ra and ^{228}Ra and their daughters, as calculated by the method of Spiers (577), are presented in table 9.

(iv) *Radon-222, Radon-220, and their short-lived decay products*

a. *Concentrations in the environment*

i. *Outdoor ground-level air*

93. ^{222}Rn, ^{220}Rn and their short-lived decay products constitute the main part of the radio-activity of ground-level air. The continents are the principal source of ^{222}Rn and ^{220}Rn, as the ratio of the emanation rate from the continents and from the oceans is about 500 for ^{222}Rn (82, 485), and probably much higher for ^{220}Rn. The diurnal variation of the atmospheric ^{222}Rn concentration near the ground is inversely related to the coefficient of vertical turbulent mixing (398). Con-

[4] One attocurie (aCi) equals 10^{-18} curie.

sequently, the typical diurnal ^{222}Rn concentration curve has a maximum in the early morning hours and a minimum in the afternoon (25, 179, 485, 548, 549). The ratio of the maximum to the minimum values is highest in the summer (10 or more) and lowest in the winter (549).

94. The short-lived decay products (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po) are never strictly in equilibrium with ^{222}Rn in surface air because of losses by deposition on the ground and on other obstacles and/or because of rapid diffusion of ^{222}Rn (73, 179). The activity ratio with ^{222}Rn is, in most cases, in the range 0.9-1.0 for ^{218}Po and 0.4-1.0 for ^{214}Pb and ^{214}Bi, the lowest ratio occurring in the evenings and during the first half of the night, depending on the local stability conditions in the lower atmosphere. Equilibrium is most closely approached in the morning (179, 398).

95. On a seasonal basis, variations of ^{222}Rn in the air above the continents depend not only upon atmospheric thermal stability (362, 397), but also upon the variation of the rate of emanation from soils (125, 406) and upon local meteorological conditions and distance from coast (442). The average annual values from different parts of the world (table 12) show the high variability of the ^{222}Rn concentrations.

96. ^{220}Rn (thoron) and its daughters behave in the atmosphere in the same way as ^{222}Rn and its decay products. However, their radio-active half-lives are very different and the emanation rate of ^{220}Rn from soils is the main factor controlling ^{220}Rn concentrations in ground-level air. In recent years, the ^{220}Rn-emanation rate from soils has been directly measured by several workers (129, 212, 277, 588). Their results are in the range 2.5-14.0 fCi cm^{-2} s^{-1}, which is consistent with Junge's estimated value of 5.6 fCi cm^{-2} s^{-1} based on the world-wide abundance of ^{232}Th (301). Atmospheric ^{220}Rn comes from the top six-centimetre layer of soil (588), and the exhalation is very sensitive to the soil moisture (212, 277, 588). It is much reduced if the soil is frozen and negligible if the soil is covered with snow. In dry weather the rate of emanation is highest at sunset, when convective streams develop in the soil due to the rapid cooling of its surface, and lowest at sunrise (212, 588).

97. In normal emanation conditions, the ^{220}Rn concentrations one metre above ground level are of the same order as those of ^{222}Rn (0.04-0.4 pCi l^{-1}) (179, 276). The distance covered by a ^{220}Rn atom between the point where it emanates from the ground and the point where it disintegrates being less than a kilometre (212), ^{220}Rn levels are determined by the local source and by the degree of stability of the lower layers of the atmosphere. The diurnal variation, as measured by Israel (275), exhibits a primary peak in the evening and a secondary one in the early morning. Because of the long half-life of ^{212}Pb, the daughter products of ^{220}Rn, ^{216}Po excepted, are in much lower concentrations (by a factor of 10 to 100) than ^{220}Rn near ground level (179, 564).

ii. *Indoor levels*

98. The air concentration of ^{222}Rn and its daughters indoors depends upon the concentration in outside air, upon the ^{222}Rn emanation rate from the walls, and upon the ventilation rate in the room. Table 13 shows the results of measurements carried out in various countries.

99. ^{222}Rn concentrations are usually higher indoors than outdoors; they are expected to be close to the values found outside if the rooms are efficiently ventilated, as in air-conditioned buildings, or if the emanation rate from the walls and the floor is low, as may be the case in wooden houses. High concentrations are found in rooms with very poor ventilation, for example in some basements, where the ^{222}Rn level will be proportional to the emanation rate from the walls, which in turn varies according to such parameters as the origin, nature, and porosity of the building material, and the type of paint or covering layer (649, 680). Between those extremes, average concentrations several times higher than those recorded outside are observed in naturally-ventilated brick, aggregate, or concrete buildings, the measured levels being sensitive to the actual degree of ventilation, which is connected to the individual habits of the inhabitants, and to the emanation rate from the walls (227, 498).

100. The degree of equilibrium of the ^{222}Rn decay products indoors is expected to be ruled by the ventilation rate, the equilibrium being nearly reached in rooms with poor ventilation, and highly perturbed in efficiently ventilated buildings. In naturally-ventilated rooms, the equilibrium conditions should be about the same as outside (555).

101. Indoor concentrations of ^{220}Rn and of its decay products are not likely to be higher than outdoors as papering or painting the walls prevents significant releases of ^{220}Rn on account of its short half-life. However, high concentrations have been observed in houses in monazite sand regions of Brazil (492).

iii. *Water*

102. Well away from the air-sea and sediment-sea interfaces, the activity concentration of ^{222}Rn in oceans is equal to that of its parent, ^{226}Ra. Even though its emanation rate is small, ^{222}Rn is not in equilibrium with ^{226}Ra near the surface. Its mean concentration at a depth of one metre is around 0.02 pCi l^{-1} (81, 84). In fresh waters ^{222}Rn levels do not show any relation with the ^{226}Ra levels. Their concentrations range from less than 1 pCi l^{-1} in some surface waters to more than 5 10^5 pCi l^{-1} in certain spa waters (111). A few nanocuries per litre seems to be a typical activity concentration for ground water (302, 571, 638). Boiling will remove most of the ^{222}Rn from water.

b. *Transfer to man and doses*

i. *Inhalation*

103. The radiation dose to the respiratory tract due to inhalation of ^{220}Rn and ^{222}Rn is negligibly small compared with that due to inhalation of their decay products, which deposit and build up in the respiratory system. The ^{222}Rn daughters are believed to be responsible for the greater rate of lung cancer among the underground uranium miners than among the general population (169). Since the observed lung cancers appear to arise primarily in the bronchi near the hilus of the lung, most authors concerned with the dosimetric aspect of the inhalation of radon daughters assume the relevant biological target to be the basal-cell layer of the bronchial tree and take into account a detailed structure of the deposition pattern along the respiratory tract. In order to calculate the dose received by the different parts of the respiratory system, the fol-

lowing factors have to be assessed: (*a*) the relative distribution of daughter products inhaled as "free" ions or atoms, or attached to aerosol particles of various sizes; (*b*) the pattern of deposition in the respiratory system and of translocation before decay; and (*c*) the distribution in the mucous layer and the thickness of the epithelial tissue separating the alpha particles emitted from their biological target.

(1) *Size distribution*

104. Radon decay products attach quickly to the aerosol particles present in the atmosphere, forming a radio-active aerosol. The unattached and the attached decay products form two very distinct groups on account of their marked difference in geometric size.

105. The attached ^{222}Rn daughters have a particle-size distribution which depends on the size distribution of the stable aerosols, as the attachment of daughters to particles seems to be related to the surface area of the aerosol particles (514, 626). Among the experimental data available on the distribution of natural radio-activity on aerosol particles (432, 572, 587), those of Mohnen and Stierstadt (432) are representative of the average. According to them, the mean value of the radius of the carrier aerosol is 25 nanometres with a 6-200 nanometre range at a concentration of 3 10^4 particles per cubic centimetre (226).

106. The unattached ^{222}Rn-daughter products which, at their formation, are heavy metal ions, are likely to form molecule clusters with water, oxygen, or carbon dioxide (301). From their observed diffusion coefficient ($D = 0.05$ cm^2 s^{-1}) it can be inferred (514) that their effective radius is 0.4 nanometre, which is well below the size of the aerosols carrying the attached daughter products. The only measurements of the fraction of unattached ^{218}Po in open air are those of Duggan and Howell (148) who found a range from 7 to 40 per cent with a mean value of 25 per cent. These results agree rather well with theoretical expectations (226, 301, 514).

107. There is no indication that the fraction of unattached ^{218}Po is consistently higher or lower indoors than outdoors (148). As for ^{214}Pb and ^{214}Bi, the unattached fraction is 2 per cent at best, as recent measurements show that there is practically no net removal of attached ^{218}Po from the aerosol (238). In the ^{220}Rn series, the fraction of unattached ^{212}Pb has been found to be about 2 per cent (239) and the size distribution of the ^{212}Pb-carrier aerosol, compared with ^{214}Pb, is slightly shifted toward larger particle sizes (282, 526).

(2) *Lung deposition and clearance*

108. Figure IX taken from Morrow (436) represents average deposition probabilities as a function of size for a man breathing normally under sedentary conditions. The deposition probabilities for the submicronic size range are theoretical. Experimentally, George and Breslin (190) found that the average values of nasal deposition of unattached and attached daughters are 62 per cent and 2 per cent, respectively. Those values agree very well with the theoretical curve and show that the contribution of the unattached ^{218}Po to lung dose is less than what was previously thought (14, 282).

109. Since alpha particles are the main contributor to the dose, regional deposition in the lower respiratory

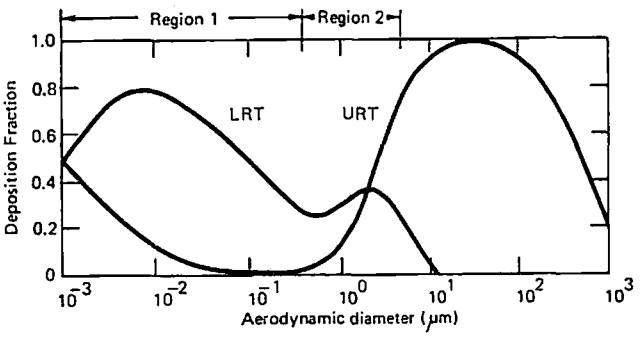


Figure IX. Deposition probabilities for particles from nearly molecular dimensions to those in the visible range. The two respiratory divisions, URT and LRT, denote upper and lower respiratory tracts, respectively; URT is equivalent to the supraglottic airways, whereas LRT is the tracheo-bronchial tree and parenchyma (436). The aerosol carriers of radon daughters are found in region 1; region 2 is the zone of industrial aerosols

tract has to be evaluated and more elaborate models than the one put forth by the ICRP Task Group on lung dynamics (268) have to be used. Landahl's model (350) was used by Jacobi (282) and by Altshuler *et al.* (14) in their extensive studies of the dose to the human respiratory tract from the inhalation of short-lived ^{222}Rn decay products. Improvements on these studies were achieved recently (226, 238): using Weibel's dichotomous lung model (644) (table 14), the depositions in the various parts of the lung were inferred from the equations of Gormley and Kennedy (206). In the range of aerosol sizes considered, the calculations show that the bigger the particle, the less it is deposited in the tracheo-bronchial tree and the lower is the total deposition (238).

110. The use of Gormley and Kennedy's equations implies that the airways are tubes of constant cross-section and that the flow is laminar. In fact, airway diameters are a function of the degree of lung inflation, vary in size from one subject to another, and may not be circular at all (367). As for the assumption of a laminar flow, experiments made with the help of a plastic model of the upper bronchial tree show that turbulent mixing occurs in the trachea and larger bronchi, resulting in a higher deposition probability and in high local deposition values around the branchings (283).

111. Moreover, total respiratory deposition of radon daughters measured in subjects breathing normal laboratory air was found to range from 25 to 45 per cent (190), which is lower than the value of about 70 per cent predicted by the ICRP Task Group on lung dynamics (268). This discrepancy has been partly explained by a rapid growth of the attached decay products in the respiratory tract due to the high humidity present. This effect, which has been found to increase the size of the small particles (up to 60 nm in diameter) by a factor of two, has not been taken into account in the regional deposition studies. The tidal volume also has an influence on the total-deposition value, whereas the respiratory frequency does not (190).

112. The rapid clearance mechanism of the deposited aerosols in the tracheo-bronchial tree is due to the movement of the mucous sheath. Studies of transit times have established that daughters deposited in each region are carried by the mucus, eventually to disinte-

grate at a site nearer to the mouth. However, in terminal bronchioles, the mucus transit time is so long that the decay products are assumed to disintegrate at the deposition site.

113. Because of the long half-lives of ^{220}Rn daughters, lung clearance mechanisms will play an important role. More than 90 per cent of the ^{212}Pb atoms deposited in the bronchial tree are eliminated by swallowing before their decay (436). Those deposited in the pulmonary region are transferred to the blood with a biological half-life of around 10 hours (71, 257, 282) which means that about half of the potential decay energy of ^{212}Pb is expended outside the lung, whereas the corresponding figure for ^{214}Pb is only 4 per cent. In the blood, about one half of the ^{212}Pb atoms are fixed by the circulating red cells and the other half distributed to other tissues (258).

(3) *Distance to the biological target*

114. The dose rate to the basal cells of the epithelial tissue depends on the distribution of the daughter products in the mucous layer and on the thickness of the epithelial tissue. The alpha-stopping power in tissue, as inferred from measurements of attenuation in polycarbonate or in gas mixtures, shows a remarkable agreement with the theoretical stopping powers and can be considered to be precisely known (238).

115. The distribution of ^{222}Rn daughters within the mucous layer of rabbits and dogs has been recently determined (669). For rabbit trachea the mucous thickness was 10 micrometres. In the dog trachea and bronchus, 30 per cent of the total ^{214}Po activity was found in the first two micrometres of mucus. Activity was estimated to extend throughout the layer with no cut-off point below the surface. Although these data may not strictly apply to the human respiratory tract, they suggest that most of the activity may stay in the top half of the mucous layer, the total thickness of which is about 14 micrometres in man (14).

116. The measured thicknesses of the epithelial bronchial tissues of a single adult man were found to vary considerably in each class of bronchus. In segmental bronchi, an exceptionally low value of thickness was 29 micrometres and the median thickness 56 micrometres. Assuming a distance of 7 micrometres from the basal cell nuclei to the basement membrane, the radon daughter products present in the segmental bronchi are on the average about 60 micrometres away from the basal cell nuclei but may be as close as 22 micrometres if the tissue is exceptionally thin. These dimensions are to be compared with the alpha-particle ranges of ^{218}Po and ^{214}Po, which are 47 and 71 micrometres, respectively.

(4) *Doses*

117. The models predict that the basal-cell nuclei which receive the highest dose in the tracheo-bronchial tree are those of the segmental bronchi, which is the region of known cancer incidence among uranium miners. Table 15 presents calculated (226) dose rates to the basal-cell layer of that area for various environments as a function of the distance from the basal cells to the ^{222}Rn daughters present in the mucous layer. The values correspond to mouth breathing with an inhalation rate of 10.4 l min^{-1} in the living accommodation and 20.8 l min^{-1} at the working site. Assuming that the average distance from the basal cells to the ^{222}Rn daughters is 60 micrometres, the annual radiation doses, calculated as the sum of the doses received in the living accommodation and at the working site, are in the range 55-195 mrad y^{-1}, but they might be as high as 520 or as low as 2 mrad y^{-1} if that distance is 45 or 70 micrometres. Therefore, wide variations will occur locally because of the variability in the thickness of the bronchial epithelium and also because of the non-uniform deposition pattern of the radon daughters, but it cannot be stated whether those variations affect the over-all hazard to the tracheo-bronchial tree, as the highest local dose rates are of the order of 1 rad y^{-1} only. It should be noted that the annual dose averaged over the mass of the tracheo-bronchial tree is about 15 millirads.

118. The dose rate to the alveolar region is of the order of 5 mrad y^{-1}; it is averaged over the mass of the alveolar tissue as the thickness of the walls of the alveoli and the diameter of the blood capillaries are small compared to the range of the alpha particles considered. The doses to organs and tissues outside the respiratory system, presented in table 16, have been measured in guinea-pigs (511); as the ventilation volume and the weight of blood are almost the same for man and for guinea-pig when divided by their respective body weight (510), the results are an estimate of the doses in man. The doses to all organs and tissues are much lower than the dose to the alveoli.

119. The doses received from inhalation of ^{220}Rn and its decay products are much lower than those due to ^{222}Rn daughters and have been the object of less attention. As in the case of ^{222}Rn, the highest dose delivered is that to the segmental bronchi, but the dose to the alveoli is less by only a factor of five (282). Assuming that the mean indoors concentration of ^{212}Pb and ^{212}Bi is 3 fCi l^{-1}, the average dose rate to the basal-cell nuclei of the segmental bronchi is calculated as 4 mrad y^{-1} while the dose rate to the alveolar tissue is 0.8 mrad y^{-1}. The doses to the other organs and tissues, as estimated from experiments on guinea-pigs, are given in table 16 (510).

ii. *Ingestion*

120. As mentioned by the Committee in its 1966 report, the ingestion of one microcurie of ^{222}Rn dissolved in water leads to a dose to the stomach of about 20 millirads, the doses to the other organs being lower by at least an order of magnitude. Assuming a consumption of 0.3 l d^{-1} of fresh water containing 1 nCi l^{-1}, the annual dose to the stomach is about 2 millirads. Another, but much lower, source of ^{222}Rn is milk, which in Sweden was found to contain about 40 times less ^{222}Rn than drinking water (364, 389).

(v) *Radon-222 long-lived decay products*

a. *^{210}Pb and ^{210}Po in the environment*

121. The main source of ^{210}Pb and its decay product ^{210}Po in the atmosphere is ^{222}Rn which emanates from the ground. The average concentration of ^{210}Pb in ground-level air at a given locality depends on the ^{222}Rn-emanation rate at that point and on the global pattern of air circulation. The observed concentrations are higher above the continents and in the northern middle latitudes, where the proportion of the land surfaces from which ^{222}Rn emanates is greater than in the other latitude bands. For some locations, ^{210}Pb

levels exhibit a seasonal variation with maximum values in winter explained either by the occurrence of long periods of stable air masses (298, 299) or by other climatological factors (557). The $^{210}Pb/^{222}Rn$ activity concentration ratios found at a site in the Soviet Union (25) are fairly constant and lie in the range $0.5\ 10^{-4}$-$1\ 10^{-4}$. The average values of this ratio for other locations vary from $0.2\ 10^{-4}$ to $2.5\ 10^{-4}$ (484). The $^{210}Po/^{210}Pb$ activity concentration ratios in ground-level air usually range from 0.05 to 0.30 but ratios greater than unity are found in industrial regions (487), which implies that a significant amount of ^{210}Po is released from coal burning. It is estimated (487) that in the latitude zone between 40° N and 60° N, the quantity of "artificial" ^{210}Po is about 10 to 20 per cent of that arising naturally. Karol (312) calculated that the total contents of ^{210}Pb and ^{210}Po in the atmosphere are from 20 to 26 and from 2.4 to 5.7 kilocuries, respectively. There is no thorough study of the average size of the aerosols to which ^{210}Pb and ^{210}Po are attached. This size has been reported to be intermediate between that of short-lived ^{222}Rn daughters and that of long-lived fission products (371). Skewed distributions have been found with 120 and 160 nanometres as geometric mean diameters (559).

122. The annual rain deposition rate of ^{210}Pb, measured in the United Kingdom (489), in India (299), and in New Zealand (447), is on the average of 3 mCi km^{-2}, which implies an activity of about 80 mCi km^{-2} in the upper layers of the soil under equilibrium conditions. The levels of ^{210}Pb in rainwater are of the order of 1-5 pCi l^{-1} (289, 489) while those of ^{210}Po are 5 to 10 times less (96, 399). The mean residence time of ^{210}Pb in the troposphere, calculated from the $^{210}Po/^{210}Pb$-activity-concentration ratio under the assumption that there is no significant ground-level source of ^{210}Po has been found to be of the order of 10 days (181). In surface waters, the ^{210}Pb concentrations are lower by a factor of 10 to 100 than those usually found in rainwater; however, concentrations in ^{222}Rn-rich waters such as mineral waters or some well waters may reach the levels found in rainwater (288, 571).

b. *Intake by man*

i. *Inhalation*

123. The average concentrations of ^{210}Pb and ^{210}Po in ground-level air in the northern middle latitudes are around 15 and 1.5 fCi m^{-3}, respectively. Assuming an intake of 20 cubic metres of air in 24 hours, 0.3 picocurie of ^{210}Pb and 0.03 picocurie of ^{210}Po are thus inhaled every day. Using a coefficient of transfer to the blood of 0.30 (437), the amounts of ^{210}Pb and ^{210}Po reaching the blood are less than 0.1 pCi d^{-1}. An additional intake may result from cigarette smoking (171, 250). Both ^{210}Pb and ^{210}Po are present in cigarette smoke, ^{210}Po being more abundant because of its higher volatility. Smoking 20 cigarettes a day leads to a daily intake of 0.3-0.8 picocurie of ^{210}Pb and 0.4-1.4 picocuries of ^{210}Po, corresponding to amounts reaching the blood of 0.2 and 0.3 pCi d^{-1} if the same transfer coefficient as above is used. However, it should be remembered that the conditions of inhalation and possibly the particle-size distributions are very different from those in normal respiration.

ii. *Ingestion*

124. For non-smokers, food usually represents the main route of uptake of both ^{210}Pb and ^{210}Po by man. Table 17 shows the values of the daily dietary intake in some countries. In the so-called western-type diet characterized by a high consumption of milk, the ^{210}Pb content is in the range 1-10 pCi d^{-1}, bread, meat, and vegetables contributing about the same amount. In that type of diet, the $^{210}Po/^{210}Pb$ ratio is about one (200, 247). An intake of 5 pCi d^{-1} leads to 0.4 and 0.3 picocurie of ^{210}Pb and ^{210}Po reaching the blood per day, assuming a gastro-intestinal fractional uptake of 0.08 and 0.06, respectively (266).

125. The $^{210}Po/^{210}Pb$ ratio may be much greater than one in animal muscle and in sea food (35, 318, 320, 553), and people whose diet consists mainly of meat or fish are expected to ingest relatively large amounts of ^{210}Po. The high ^{210}Po dietary intake of the Lapps is due to the special lichen-reindeer-man food chain, ^{210}Po accumulating in lichens and in reindeer meat. The average intake of ^{210}Po by Lapps is more than an order of magnitude higher than by "non-arctic" populations, while the intake of ^{210}Pb is higher by only a factor of about two or three (317). In Japan, the consumption of sea food accounting for 12 pCi d^{-1} of the ^{210}Pb daily intake, it is likely that the ^{210}Po dietary intake is also much higher than that of ^{210}Pb.

iii. *Distribution in man*

126. The activity concentration of ^{210}Pb and ^{210}Po in body tissues depends mainly upon the direct intake of those elements. The contribution from other sources, such as decay of ^{226}Ra in the skeleton, decay of atmospheric ^{222}Rn dissolved in the body fluids, and decay of inhaled short-lived daughters of ^{222}Rn is relatively unimportant (249).

127. The major fraction of ^{210}Pb in man is found in bone which contains 70 per cent or more of the body burden (289, 326). In the temperate zone of the northern hemisphere, the ^{210}Pb concentration in wet bone is about 40 pCi kg^{-1} (289). In soft tissues, the highest average concentrations, typically between 5 and 10 pCi kg^{-1}, are found in liver, bladder and gonads (29, 57). An exception is constituted by hair, which, during its period of growth, concentrates ^{210}Pb in amounts higher than bone. It has been suggested that determination of ^{210}Pb in the hair may be used to assess the integral exposure to this nuclide over the previous month in case of occupational poisoning (288, 290).

128. The $^{210}Po/^{210}Pb$ activity ratio is close to unity in bone and it is likely that both the amount of ^{210}Po taken up from external sources and that fraction which decays from ^{210}Pb and ^{210}Bi have a long biological half-life in bone compared with the physical half-life (457). In some soft tissues such as the bladder, the $^{210}Po/^{210}Pb$ activity ratio is lower than one, whereas it is greater than one in others, for example the lung, the liver and the kidney (29, 57). The reason for the excess of ^{210}Po in those tissues is not clear; it has been suggested (247) that the uptake and the metabolic behaviour of polonium might be related to the chemical form in which the dietary ^{210}Po occurs. Because the concentrations of ^{210}Po in hair, bone tissue and liver of naturally-exposed people show some correlation, hair monitoring has been proposed as a convenient way of assessing the ^{210}Po concentration in bone (18).

129. Comparative studies between smokers and non-smokers (27, 57, 246) show that the concentrations of ^{210}Pb and ^{210}Po in the lungs and ribs of ciga-

rette smokers are about two or three times higher than in non-smokers. In the soft tissues other than lung, the contribution of cigarette smoke to the ^{210}Pb and ^{210}Po content is less important (28).

130. High concentrations of ^{210}Pb and especially of ^{210}Po are to be expected in tissues of arctic populations consuming reindeer or caribou meat. The values observed in samples from Alaskan residents who had not eaten any caribou meat are within the normal range of values reported for unexposed populations while the soft tissue concentrations of ^{210}Po and the ^{210}Po/^{210}Pb activity ratio were found to increase with consumption of caribou meat (58). However, none of the individuals studied consumed caribou meat daily. The distribution of ^{210}Pb and ^{210}Po in the tissues of such a person, which would be very valuable, has not been measured yet owing to the difficulty of obtaining autopsy tissue samples. However, analyses of teeth of Lapps who breed reindeer showed ^{210}Pb and ^{210}Po concentrations about twice those of southern Finns, who are representative of a non-arctic western population. In blood and placenta, ^{210}Pb and ^{210}Po are 2 and 12 times higher, respectively, in the former than in the latter population (317). It has been assumed that the polonium concentration in gonads would also be 12 times higher in Lapps than in southern Finns.

iv. *Doses*

131. The radiation dose absorbed by the body tissues from the ^{210}Pb chain depends mainly on the highly energetic alpha particles of ^{210}Po. At equilibrium, the contribution from the beta emission of ^{210}Pb and ^{210}Bi is only 7.5 per cent of that from ^{210}Po and will be neglected here. Because ^{210}Po concentrations in the gonads are higher than once believed, the corresponding dose rates may be higher by a factor of two than those estimated by the Committee in its 1966 report. Lapps might receive an annual genetic dose of 8.5 millirads from this source (317). The annual doses to the bone tissues of the northern temperate latitudes population (table 9), calculated by the method of Spiers (577), are 4.0 millirads for osteocytes, 2.4 millirads for cells lining Haversian canals, 1.6 millirads for cells lying near the endosteal surfaces in trabecular bone, and 0.3 millirad for the whole marrow, if the concentration activity of ^{210}Po in bone is taken to be 40 pCi kg^{-1} (289). In the lung, the annual average dose is of the order of 0.5 to 1 millirad but ^{210}Po has been found in very high concentrations in the bronchial epithelium of the segmental bifurcations of heavy smokers, implying local doses two orders of magnitude higher than the average (369).

B. EXTERNAL IRRADIATION

132. When present in the top few centimetres of the earth, nuclides of the natural radio-active series, together with ^{40}K (relative abundance 0.01 per cent), give rise to gamma radiation near the earth's surface. The doses from this radiation are lowest on the surfaces of oceans or lakes. The concentration of these natural radio-nuclides varies greatly between different types of rocks and soils, being highest in igneous rocks such as granite and lowest in sedimentary rocks, such as limestone and sandstone (563, 616). These radionuclides can also give rise to external radiation doses to man when present in the materials used to construct buildings and to pave roadways. The gamma radiation above the ground can be affected by the moisture content of the soil and, in particular, by snow cover. The effect of snow cover in reducing the natural radiation is illustrated in figure X, which shows the external gamma radiation measured at two sites in Sweden between 1960 and 1971.

133. The dose rate in air from gamma radiation has been determined using both gamma-ray spectroscopy and ionization chamber measurements. In the latter case, it is necessary to subtract the cosmic-ray contribution to obtain the external gamma dose. The

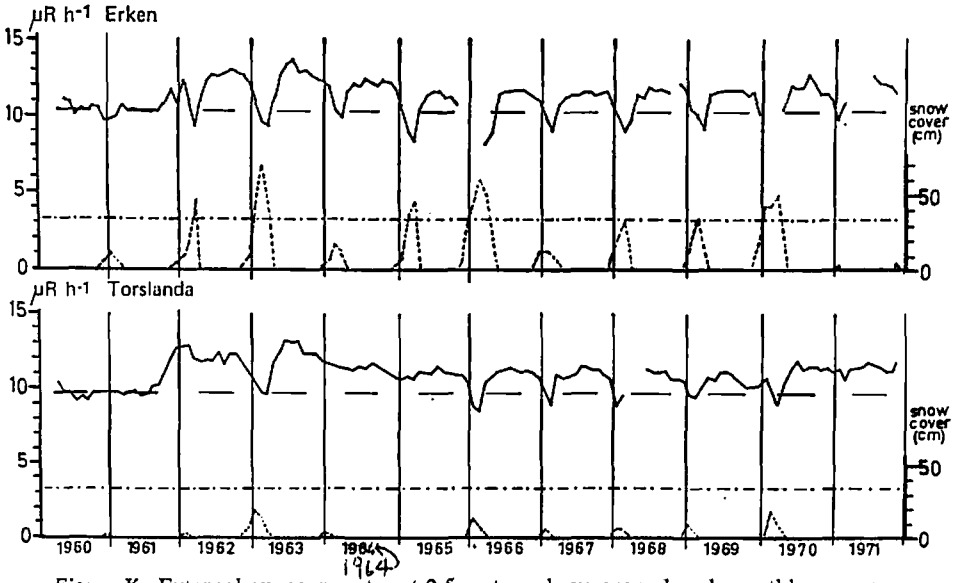


Figure X. External exposure rates at 2.5 metres above ground and monthly averages of the snow cover in Sweden (390, 596)

——— Total external exposure
— — — Exposure level summer 1960 and 1961
— · — · — · — Average exposure from cosmic rays
. . . . . Snow cover (scale on the right)

resulting gamma dose rate includes a contribution from radon, thoron and their daughter products present in the air estimated to be from 2 to 3 mrad y^{-1} (563, 615).

134. The dose rates obtained from recent surveys carried out in 12 countries are summarized in table 18, where the results of measurements made both indoors and outdoors are shown. Although individual measurements cover a range up to 400 mrad y^{-1}, the average for the different regions of normal background are much more closely grouped. The average indoor and outdoor dose rates for the three country-wide surveys reported in table 18 show that a representative value would be about 60 mrad y^{-1}.

135. In the United States survey (37), 90 per cent of the populated areas had annual doses ranging between 30 and 95 millirads. The results of this survey also showed that ^{40}K, the ^{238}U series and ^{232}Th series contributed 17, 13 and 25 millirads, respectively, to the average annual dose of 55 millirads.

136. In the United States, the German Democratic Republic and Italy, average dose rates indoors were lower than outside, while in the United Kingdom and the Federal Republic of Germany they were higher indoors. In most other countries, there was little difference in the average indoor and outdoor dose rate. The shielding offered by building structures is often offset by radiation due to natural radio-nuclides present in the building material. In New England, where homes are of wood construction, Lowder *et al.* (378) found that typical radiation levels were about 70 per cent of those outside, while in brick houses in Edinburgh, U.K., Spiers (579) found that dose rates were higher indoors.

137. At certain sites, the terrestrial gamma dose rate is very low. Thus Beck *et al.* (39) have reported measurements over lakes and reservoirs in the United States where the dose rate was less than 4 mrad y^{-1}, while Liboff and Shamos (360) reported levels as low as 0.4 mrad y^{-1} in certain mines in the United States and Canada.

138. There are also several areas of the world where high concentrations of thorium and uranium occur in the surface layers of the earth and result in greatly enhanced gamma dose rates. In the coastal regions of the Indian state of Kerala, there are patches of sand containing monazite, a mineral which may contain high concentrations of thorium and uranium. This mineral also occurs in some coastal areas of Brazil, as well as in China and the United States (563).

139. High radiation exposures are also to be found in the regions of volcanic intrusives in the State of Minas Gerais in Brazil (493).

140. Gopal-Ayengar *et al.* (204, 205) carried out a dosimetric survey on a 55-kilometre-long coastal strip, inhabited by some 70,000 people, in the state of Kerala, India. By issuing thermoluminescent dosemeters, which were worn for two months, the radiation exposures of 8,513 individuals living in 2,374 households were obtained. On the basis of these data, it was estimated that, of the 70,000 inhabitants of that area, 16,600 received annual doses of more than 0.5 rad and that, of these, 4,500 and 470 received more than one and two rads, respectively.

141. In the towns of Guarapari and Meaipe, on the Brazilian coast, it was estimated that some 20,000 inhabitants are exposed to levels of external radiation from monazite sands that vary from 0.2 to 8 rad y^{-1} (493). By issuing 317 inhabitants of Guarapari with thermoluminescent dosemeters for three months, Cullen (131) determined the average dose rate of the group as 0.55 rad y^{-1} with a range of 0.09 to 2.8 rad y^{-1}. Penna-Franca *et al.* (493) also measured external radiation dose rates on a hill near the city of Pocos de Caldas, which presents the highest levels of radiation in the Brazilian volcanic region. The air dose rates were in the range of 0.43 to 25 rad y^{-1}, with many sites having rates of 7 rad y^{-1}. However, this hill has a small area and is uninhabited.

142. All the dose rates quoted so far for gamma radiation are air dose rates. To convert these to dose rates in tissue, say bone or muscle, they must be multiplied by the ratio of the mass absorption coefficient in tissue to that in air. Johns and Cunningham (295) have tabulated this ratio for both hard bone and muscle. For 0.5-10-MeV gamma rays, this ratio is in the range of 1.07-1.11. In order to compute doses to the bone and gonads we will use the value 1.10 given by the ICRU for these energies (270).

143. Bennett (49) investigated the procedures for converting air exposure measurements into absorbed doses to the reproductive organs. He used computed gamma-ray spectra above the ground for both plane and exponential distributions in soil of ^{238}U, ^{232}Th and their daughters and of ^{40}K and ^{137}Cs. In obtaining the gonad dose from a uniform exposure around the body, actual anatomical drawings of body cross-sections were used to account for shielding by overlying tissue and bone. The resulting average conversion factor obtained (gonad/air) was 0.82. It should be noted that this factor already contains the tissue/air dose factor of 1.1 mentioned in the last paragraph. Conversion factors calculated by Bennett (49) and those based upon phantom measurements by Jones (297) are given in table 19 for exposures to gamma rays from natural emitters and from ^{137}Cs. The average conversion factors for testes and ovaries are fairly constant and therefore little error will be involved in applying a uniform factor of 0.8. From the work of Jones (297) it appears that the appropriate screening factors relating the absorbed dose in bone marrow to the free air dose is also 0.8. Since the above factor refers to 2π geometry, it is applicable to gamma-radiation received outdoors.

144. Spiers and Overton (578) determined screening factors using a phantom irradiated in 3π geometry. They obtained values of 0.63 and 0.64 for the exposure of gonads and bone marrow to external radiation. These factors are just screening factors and do not contain the tissue/air dose-conversion factor. Applying the tissue/air dose-conversion factor a value of 0.7 is obtained for the average gonad and bone-marrow dose. By using this factor of 0.7 for indoor exposure and 0.8 for outdoor exposure and assuming that 7 hours per day is spent outdoors, an average conversion factor of 0.73 is obtained. The product of the average air dose rate (60 mrad y^{-1}) and the average conversion factor (0.73) gives a value for the gonad and bone marrow dose rates of 44 mrad y^{-1}. This figure does not differ significantly from the value of 50 mrad y^{-1} previously used by the Committee.

III. Recapitulation of dose rates

145. Table 20 summarizes the contribution of natural sources to the radiation exposure of human populations. The three tissues considered are the gonads, the bone marrow and the bone-lining cells. For comparison, table 20 includes the estimates for the gonads and the bone marrow given in the 1966 report.

146. In addition to the doses included in table 20, yearly doses in the range 50-200 millirads are received by the basal epithelial cells of segmental bronchi from inhaled radon daughters. Their actual values are still uncertain owing to the many assumptions that underlie the estimates.

Part Two. Man-made environmental radiation

I. Nuclear explosions

A. Atmospheric and surface explosions

147. More than any other subject, radio-active contamination of the environment by nuclear test explosions has been a matter of continued interest for the Committee. When the Committee prepared its first comprehensive report in 1958, very little was known about the movements of artificial radio-activity through the biosphere and only some of the nuclides released into the environment by atmospheric and surface explosions were being monitored and considered worth studying.

148. The amount of information available has grown over the years, as the pace of atmospheric injections reached its peak in 1961-1962 and declined to its current comparatively low levels. The present review will largely be devoted to an assessment of current radio-active contamination from all tests, and the reader is referred to earlier reports for a record of the situation as it changed with time. However, a certain amount of background information previously discussed by the Committee is included in this review so as to make it reasonably self-contained.

149. After a description of transport mechanisms in the atmosphere, which largely summarizes the discussion in the 1964 report, the transport of individual nuclides in the biosphere and the resulting doses will be discussed, followed by a review of external radiation from radio-nuclides deposited on the ground and by a summary of the dose commitments arising from all nuclear tests.

1. *Transport of radio-active debris within the atmosphere*

150. After an atmospheric explosion, the fission products and construction material contained within the fireball are initially present in gaseous form. As the fireball rises and cools, particle formation takes place through condensation and coagulation. The resulting particles are small and consist mainly of material from the nuclear device and its carrier.

151. With surface explosions and explosions at such heights that the fireball touches the ground, large amounts of fragmented ground material will be incorporated in the fireball and become melted and partly vaporized. Some of the vaporized material forms particles by condensation and coagulation, in the same way as with atmospheric explosions, but most of it will condense on the surface of melted ground particles.

152. The dependence on total yield of the altitude of both the top and base of the stabilized cloud (the mushroom) for surface explosions and atmospheric explosions below an altitude of three kilometres is shown in figure XI (506). The initial vertical distribution of radio-activity within the cloud is shown in table 21 (506). The total amount of radio-activity injected into the stratosphere by a surface explosion is about one half of that from an atmospheric explosion of the same yield.

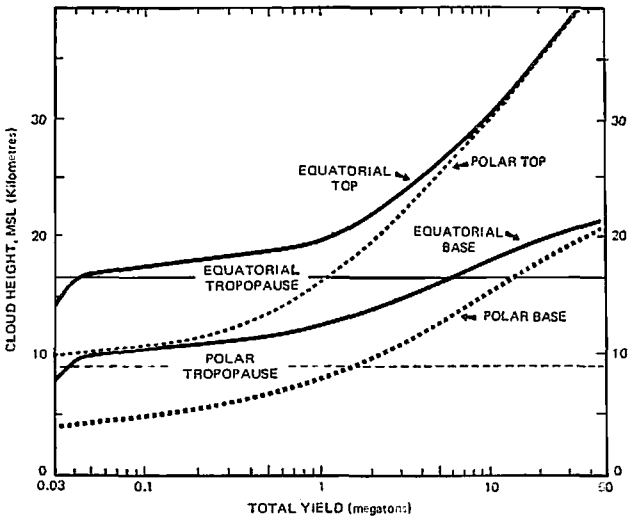


Figure XI. "Mushroom cap" cloud top and base as a function of total yield of device. "Equatorial" refers to 0-30° latitude; "polar" refers to 30-90° (506)

153. Although our knowledge of air movement in the atmosphere is incomplete in certain respects, particularly at high altitudes, some basic features of this motion are fairly well established. One marked feature of atmospheric circulation is the system of westerly jet streams situated in mid-latitudes at altitudes of about 10 kilometres (figure XII). Velocities of 100-300 kilometres per hour are usual in these regions. In middle and higher latitudes air is carried around the

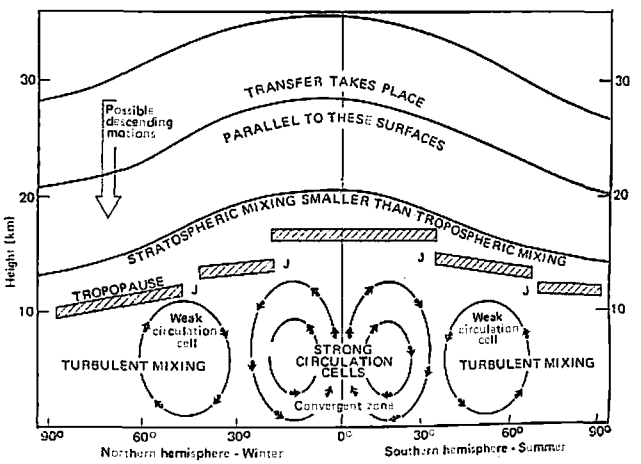


Figure XII. Schematic cross-section displaying characteristics of meridional transport ("J" locates typical jet stream positions) (614)

globe in a week or so and in one to two months in tropical regions (66). Since, in the stratosphere, these times are short compared to transfer times in the meridional and vertical directions, the debris may be considered to be zonally well mixed so that, several months after a test, they will be uniformly distributed around a circle of latitude (66). In the troposphere, vertical motions are rapid but in the lower stratosphere these vertical motions and hence the associated vertical transport are much smaller (66, 509).

(a) *Movement within the stratosphere*

154. Observations of radio-active tracers have contributed greatly to the understanding of air movement within the stratosphere. A schematic representation of the stratospheric circulation features deduced from data on ^{90}Sr, ^{14}C, ^{185}W, ^{102}Rh, ^{109}Cd and ^{238}Pu is shown in figure XIII (368). Tracer data above about 37 kilo-

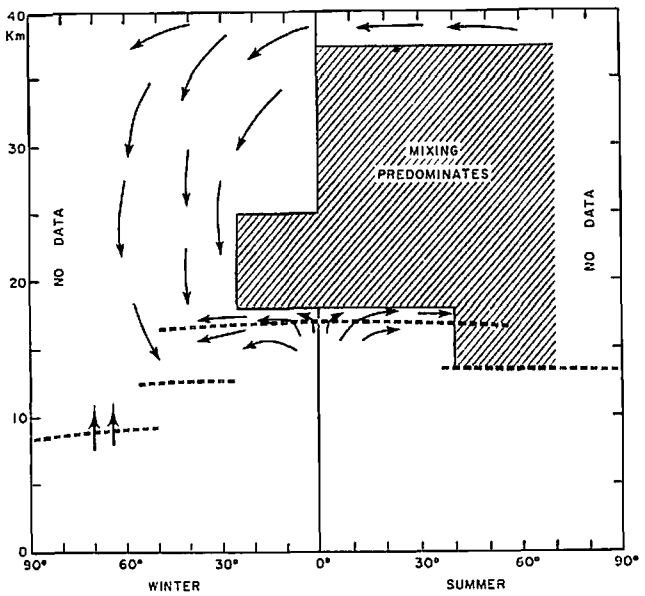


Figure XIII. Schematic representation of the stratospheric circulation as deduced from radio-active tracer data (368)

metres between 25° and 70° indicate a flow from the summer hemisphere to the winter hemisphere and a mean descending motion in the winter stratosphere. Ascending motions occur near the equatorial tropopause and poleward motions in the lower winter stratosphere at latitudes higher than 70°. Virtually the entire summer stratosphere and the winter stratosphere below 25° between 18 and 25 kilometres are dominated by mixing processes with no evidence of organized circulations in the meridional phase.

155. The level of maximum concentration of radio-active tracer material injected into the stratosphere slopes from higher altitudes over the equator to lower altitudes and colder potential temperatures near the pole (386). Six to twelve months after the injection into the lower stratosphere in equatorial, temperate and polar latitudes, the configuration of the levels of maximum concentrations was found to be almost identical irrespective of the latitude and altitude of injection and of the vertical distribution of the debris. Tracers originally injected into the upper stratosphere and aerosphere follow a similar pattern. Machta *et al.* (386) suggest the following genesis of the surface of maximum concentration as deduced from data on radio-active debris from the nuclear explosion at 40° N of 17 June 1967:

(*a*) a poleward, essentially horizontal, displacement of most of the air containing the debris by mid-autumn, accompanied by a warming of the order of 0.2° C per day;

(*b*) a net descending motion during late autumn and winter north of about 55° N at a rate of 1-5 kilometres per month with the air cooling by about 1° C per day;

(*c*) isolated patches of debris remaining near the source region;

(*d*) quasi-horizontal diffusion imposed on the mean circulation, smoothing out the gradients and resulting in a surface of maximum concentration sloping downward from about 20 kilometres at 20° N to 15 kilometres at 60° N in spring and summer.

(b) *Transfer to troposphere*

156. Many mechanisms may play a role in the transfer of particulate radio-activity from the stratosphere to the troposphere. Thus, heavy particles can settle through the tropopause but the bulk of the radio-activity in the lower stratosphere is associated with particles too small for gravitational settling to contribute significantly to the downward transport through the tropopause (614). The horizontal transport through the subtropical tropopause gap makes a considerable (and often determinant) contribution in the air mass exchange between the stratosphere and the troposphere and the well-known spring maximum concentration of fall-out in surface air is due to a winter maximum exchange between lower stratosphere and troposphere through the tropopause of temperate and high latitudes (313). Finally, stratospheric radio-activity can be incorporated into the troposphere by diffusive mixing through folds of the tropopause (133-135).

157. The concept of stratospheric mean residence time has been thoroughly discussed in the 1964 report of the Committee. It is defined as the average time spent by the radio-active debris in the stratosphere before it is transferred to the troposphere. Such a definition in no way implies that the material is well mixed within the stratosphere or that it is held up during the transfer to the troposphere (66).

158. The mean stratospheric residence time of radio-active debris produced by an explosion will depend on the explosion's altitude, latitude, and possibly its time of occurrence. Thus, fission products in lower polar stratosphere may have a mean residence time of six months or less, while debris from medium-altitude explosions has mean residence times of perhaps two to three years (300). At much higher altitudes (over 100 km) as illustrated by the ^{102}Rh experiment, the residence time increases to 5 or 10 years (307, 308, 356, 584). The mean residence time for ^{90}Sr is 1.1-1.2 years (122, 167, 337, 629) and seems to be fairly constant for all northern latitudes (167). For excess ^{14}C in the stratosphere the apparent half residence time is between two and five years (605).

(c) *Movement within the troposphere*

159. Once the radio-active debris enters the troposphere it is mixed fairly rapidly within the hemisphere

of entry since mixing by eddy diffusion and convection is much more rapid in the troposphere than in the stratosphere. In the meridional plane there are two circulation cells within each hemisphere, as shown in figure XII. The tropical cells are well developed, with air rising in equatorial regions and descending into the 20°-30° latitude region. The two cells at higher latitudes are weaker with descending air at latitudes of 40°-50° and rising air at higher latitudes. At middle and higher latitudes large-scale eddies give rise to rapid meridional transport (614).

160. In the troposphere, the exchange of particulate radio-activity across the meteorological equator is impeded for two reasons. In the first place the convergence of low-altitude air currents (figure XII) tends to keep air in the same hemisphere and also retards the exchange of gases. The second reason is the scavenging of particulates by showery precipitation in the convergent zone (614). However, several investigators have reported interhemispheric transport of tropospheric nuclear debris from southern to northern hemisphere (97, 98, 172, 216, 448, 522, 523, 542, 574) and vice versa (115, 349, 413, 651).

161. Meridional circulation seems to constitute the main mechanism responsible for this transport. The mean exchange time between hemispheres, defined as the mean time spent in the northern hemisphere by a molecule of air before transfer to the southern hemisphere and vice versa, was estimated from various gaseous tracer experiments to be about 1.5 years (614).

162. The mean residence time of nuclear debris in the troposphere is estimated to be about 30 days (96, 387, 586). Evidence suggests that particulates reside in the lower, rain-bearing, layers of the atmosphere for a period of the order of five days or less (382, 387, 402).

163. A model for predicting the atmospheric content of radio-active material has been worked out by Krey and Krajewski (337). The atmosphere of each hemisphere is divided into three compartments, i.e. the atmosphere above 21 kilometres, that below 21 kilometres, and the troposphere. Transfer between compartments follows first-order kinetics and the transfer constants used are: from above 21 kilometres to the lower stratosphere 0.116 month^{-1}, from the lower stratosphere to the troposphere 0.0693 month^{-1} and from the troposphere to ground level 0.693 month^{-1}. The debris from an injection well above 21 kilometres is equally partitioned between the hemispheres while for debris injected into the lower stratosphere there is a dynamic exchange between the hemispheres with a transfer constant of 0.0116 month^{-1}. Using this model Krey and Krajewski (337-339) have calculated stratospheric inventory, surface air concentration and deposition and found good agreement with measurements.

(d) *Deposition*

164. Mechanisms of deposition were discussed in some detail in the Committee's 1964 report. After entering the troposphere from above, fission products are transported down to the level of the rain-bearing clouds mainly by turbulent mixing. This downward movement is enhanced over anti-cyclonic systems and opposed over cyclonic systems (134). Below this level, the radio-active particles are rapidly washed out by precipitation and deposited upon the earth (346). In addition, dry removal of fission products takes place through several mechanisms. Dry removal by sedimentation requires particles to be larger than about five micrometres and is important only in local fall-out. Dry deposition of world-wide fall-out makes an important contribution to the total fall-out only in areas of low rainfall.

165. Fission products can enter rain-water by processes within the cloud, the so-called rain-out, or can be picked up by raindrops below the cloud, the so-called wash-out. For aerosols of small particle size the wash-out is relatively quite slow so that rain-out is probably the most important wet-deposition process (164, 301). The small contribution of wash-out processes to total deposition probably accounts for the fact that the activity of fission products in ground-level air does not seem to be greatly influenced by precipitation rates (162, 381, 619).

2. *Internal irradiation*

(a) *Tritium*

166. Eriksson (165) estimated that 1,900 megacuries of tritium were released into the atmosphere by tests up to 1963, most of them into the northern hemisphere. The dose commitment can be calculated using the relation,

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

where γ_0 is the dose rate from natural tritium, W is the amount of artificial tritium released into the atmosphere and B is the amount of natural tritium produced annually. The dose rate due to natural tritium of 0.6-2.5 μrad y^{-1} results from an annual production of 1.6 megacuries, that is 0.8 megacurie in each hemisphere (paragraphs 60 and 62). By assuming that all the bomb-produced tritium remains in the northern hemisphere we obtain an upper limit to the dose commitment. This will be in the range 0.6 10^{-3} (1900/0.8) = 1.4 and 2.5 10^{-3} (1900/0.8) = 5.9 millirads. If it is assumed that there is rapid (compared with the half-life) mixing of tritium between hemispheres, a lower limit to the dose commitment is obtained. This is in the range of 0.6 10^{-3} (1900/1.6) = 0.7 and 2.5 10^{-3} (1900/1.6) = 3.0 millirads. Since the movement of tritium from one hemisphere to another appears to be fairly slow the true dose commitment should be closer to the upper limit. In this report, the values used as dose commitments to the populations of the northern and of the southern hemisphere are four and one millirads, respectively.

(b) *Carbon-14*

167. The activity of ^{14}C in the CO_2 of tropospheric air of the northern and southern hemispheres is shown in figure XIV, where the ^{14}C concentrations of surface ocean waters are also shown (464, 518, 614). During 1968-1969, levels in both hemispheres remained fairly constant at about 60 per cent above normal, the ^{14}C that moved into the oceans having been replenished by the nuclear tests in 1968. The activities in surface ocean waters have risen much less than was expected and now appear to be decreasing.

168. This observation may indicate a much more rapid exchange of ^{14}C between the surface and deep

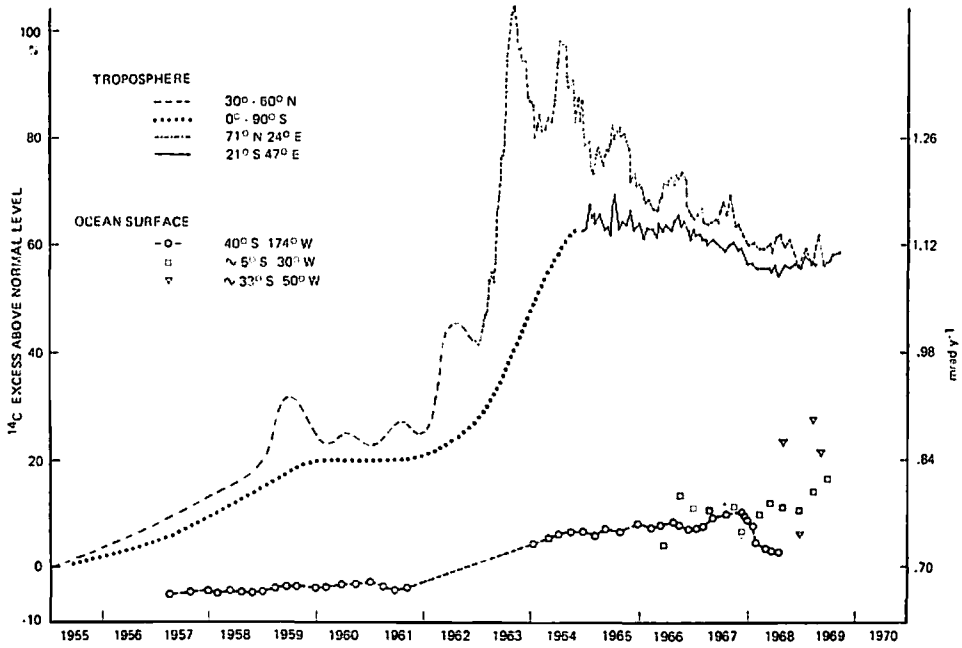


Figure XIV. Radio-carbon in the troposphere and surface ocean (464, 518, 614)

ocean than was originally predicted (518). However, the situation is not simple since the ^{14}C activity of surface ocean waters varies considerably with latitude. The value of the exchange time with the deep ocean will directly affect that part of the dose commitment from ^{14}C delivered up to the year 2000, but at this time there are not enough new data to warrant changing the estimates made by the Committee in its 1969 report.

169. Fairhall *et al.* (168) estimated that the total ^{14}C inventory from atmospheric tests was 6.2 megacuries compared to a steady state natural inventory of 280 megacuries (paragraph 64). Using the dose rates for natural ^{14}C from paragraph 67, the dose commitments, calculated in the same way as for ^{3}H, are 140 millirads to soft tissue and 170 millirads to endosteal cells.

170. Because of the long half-life of ^{14}C most of the dose commitment is delivered over a period of thousands of years. That part of the dose commitment that will be delivered up to the year 2000 can be estimated from models representing the exchange of ^{14}C between the atmosphere, the ocean and the biosphere (614, 616). The estimates calculated in the same way as in the 1969 report are 12 millirads to the gonads and bone marrow and 15 millirads to cells lining bone surfaces.

(c) *Iron-55*

171. Iron-55 is almost exclusively man-made and has been one of the major contributors to radioactivity in fall-out since the 1961-1962 series of nuclear tests. This radio-nuclide, which decays by electron capture into ^{55}Mn with a half-life of 2.6 years, is most probably produced from the stable ^{54}Fe isotope by thermal neutrons through the ^{54}Fe (n, γ) nuclear reaction and from the stable ^{56}Fe isotope by fast neutrons through the ^{56}Fe (n, 2n) reaction. The total production of ^{55}Fe from tests was estimated as 50 megacuries (248). Its activity in surface air was monitored from 1964 to 1970 at 22 sites in North and South America. Activity fell from about 500 fCi m^{-3} in 1964 to a few femtocuries per cubic metre in 1970 (633).

172. The two main routes of ^{55}Fe intake by humans are the terrestrial food chain from plant to animal to man and the marine food chain from sea-water to fish to man (280, 473). Ocean fish contains a higher concentration of ^{55}Fe than most other food-stuffs (473, 656). In man ^{55}Fe concentrates in the red blood cells, which contain 65 per cent of the body burden (280) although higher concentrations are present in haemosiderin and ferritin—two proteins that store iron (503). The body burden of many people in different parts of the world was determined in 1966 and in 1969; most of the results, which were in the range 20-30 nanocuries in 1966 (473), dropped to the 1-10 nanocuries range in 1969 (352). At Richland, in the United States, the body burden of ^{55}Fe in adults reached a peak level of about 20 nanocuries in January 1967, then started to decrease (474, 475).

173. In Alaska (United States) and in Japan, among people consuming large quantities of fish, body burdens higher than 1,000 nanocuries were observed in 1966 (473), but in 1969 ^{55}Fe in Alaskan fish-eating natives was only 10 times higher than in Richland residents and its level was declining at a more rapid rate, reflecting the much higher turn-over rate of iron in the marine biosphere (351).

174. A body burden of 30 nanocuries leads to annual doses of 1 millirad to red blood cells, 0.5 millirad to the whole blood, 0.15 millirad to the gonads and the cells lining bone surfaces, 0.08 millirad to the red bone marrow and 0.06 millirad to the whole body (503). The dose commitments in the northern hemisphere due to nuclear testing in the period 1954-1962 were estimated by Persson (503). Assuming a maximum body burden of 30 nanocuries in the temperate latitudes, the estimates are 1 millirad to the gonads and bone-lining cells and 0.6 millirad to the bone marrow. A reduction by a factor of four is assumed for the southern hemisphere.

(d) *Krypton-85*

175. The amount of ^{85}Kr produced by atmospheric nuclear explosions can be estimated at about three

megacuries from the ^{90}Sr production (discussed in paragraphs 178-182) and the $^{85}Kr/^{90}Sr$ fission-yield ratio of about 0.06. Since the greatest production occurred in 1961-1962, radio-active decay has resulted in about half the total production remaining in the atmosphere in 1970.

176. Krypton-85 is a beta emitter (maximum energy 670 keV). In 0.4 per cent of the disintegrations, it also emits a gamma photon whose energy is 514 keV. Table 22 indicates the annual doses received by an individual immersed in a cloud of ^{85}Kr with an activity concentration of 1 pCi m^{-3}. By external irradiation, beta rays deliver a dose to the skin and to the subcutaneous tissues only, while the gamma radiation is responsible for whole-body and gonad doses (149, 241). Internal irradiation also occurs as a result of inhalation; lung is then the most exposed organ, and fatty tissues receive higher doses than blood and muscle because of the greater solubility of krypton in fat than in water (610, 648). From the biological viewpoint, the dose to the gonads from external irradiation (17 nrad y^{-1} per pCi m^{-3}) is the most significant and the internal doses are comparatively negligible.

177. The distribution of ^{85}Kr being almost homogeneous over the surface of the globe and throughout the troposphere (paragraph 396), the estimated three megacuries produced by atmospheric tests correspond to a dose commitment to the gonads of about 0.2 microrad.

(e) *Radio-strontium*

(i) *Inventory*

178. The stratospheric inventory of ^{90}Sr in both hemispheres increased temporarily after the tests in 1967, 1968, 1969 and 1970 (figure XV) (340). Apart

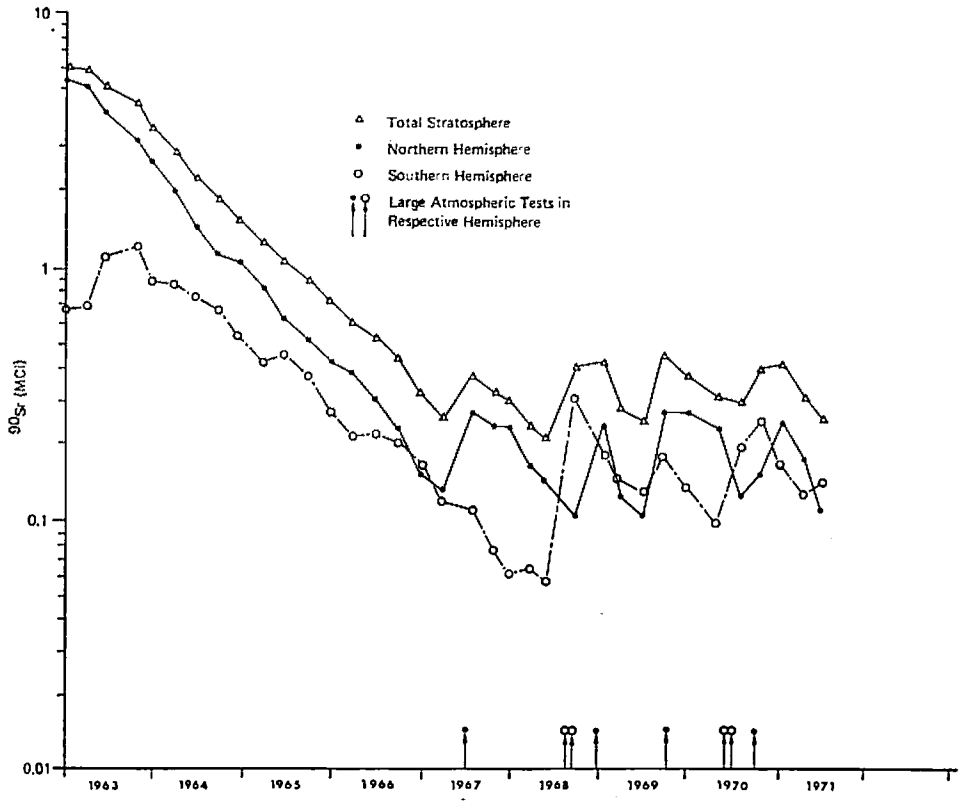


Figure XV. Stratospheric inventory of ^{90}Sr in the northern and southern hemispheres (341)

from those peaks, however, there has not been much change in the stratospheric inventory of ^{90}Sr since 1967 (table 23), the level being maintained relatively steady by the atmospheric nuclear tests carried out during the last three years. In February 1971 the inventories in the stratospheres of the northern and southern hemispheres were estimated to be 0.29 and 0.16 megacurie, respectively, most of this being due to recent tests (340).

179. The annual and cumulative deposition of ^{90}Sr in the northern and southern hemispheres are shown in table 24 for the years 1958 through 1970 (634). The global deposition in 1970 was not much greater than in 1967, 1968 and 1969, reflecting a relatively constant stratospheric inventory. The monthly deposition of ^{90}Sr in both the northern and the southern hemispheres is shown in figure XVI and the cumulative deposit for both the northern and southern hemispheres for the years 1958 through 1970 are shown in figure XVII. Measurements of the $^{89}Sr/^{90}Sr$ ratio in precipitation in the northern hemisphere gave values between one and nine for most of 1969, indicating that much of the radio-strontium was due to recent tests (99, 100, 228). In 1969 the ^{90}Sr deposition was about equally divided between the hemispheres. This is the first time that the annual fall-out in the southern hemisphere has been equal to or greater than that in the northern hemisphere (631). However, the southern hemisphere deposition in 1969-1970 was only about half that recorded in the years 1962-1965 in spite of the recent tests there (634). It can be seen from tables 23 and 24 that the global cumulative deposit of ^{90}Sr has changed little over the last few years, the annual deposition

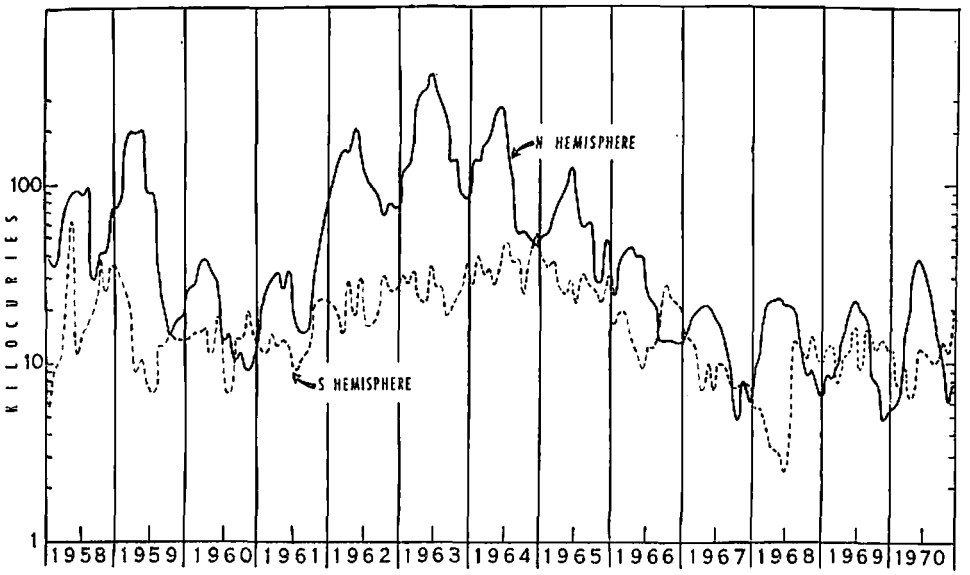


Figure XVI. Monthly ^{90}Sr deposition (634)

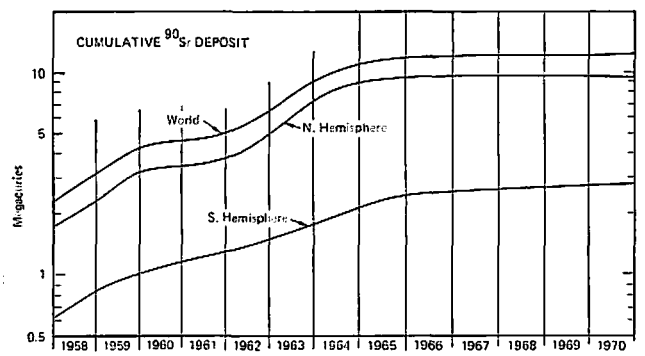


Figure XVII. Cumulative ^{90}Sr deposits (634)

being just sufficient to compensate for ^{90}Sr that has decayed on the ground.

180. It has been estimated that by mid-1969 about 70 per cent of the ^{90}Sr in the surface air of the northern hemisphere was contributed by the tests in central Asia carried out on 27 December 1968. In the southern hemisphere in mid-1969, 75 per cent of the ^{90}Sr activity in surface air is ascribed to the September tests in the south Pacific (99). The global deposition of ^{90}Sr as deduced from the measurements of the United Kingdom network showed that at the end of 1970 the cumulative deposit was 12.4 megacuries and the annual deposit for 1970, 0.21 megacurie (101). The deposition over the world was calculated by integrating the latitudinal distribution of ^{90}Sr concentration in rain weighted by the distribution of rainfall. Much of the United Kingdom data for 1968 was derived from ^{137}Cs measurements using a mean $^{137}Cs/^{90}Sr$ ratio of 1.56. These results agree with those reported from the United States network based on ^{90}Sr measurements (table 24). Traces of debris from the 1968 south Pacific tests have been detected (488) as far north as Bombay (India), Hongkong, Chilton (United Kingdom) and International Falls, Minnesota (United States).

181. In table 25 the annual deposition and average concentration of ^{90}Sr in rain is shown for four United States weather stations in the north Atlantic and also for five continental stations and for four island stations. The annual deposits at each weather station were estimated by dividing the measured deposit by the fraction of the year for which collections were made. Neither the annual deposits nor the average annual concentrations of ^{90}Sr appear to be significantly different on the weather ships and small islands than on the land-based stations. As in previous reports of the Committee, it is assumed that there is no difference between deposition over the oceans and over land.

182. In table 26 are shown the latitudinal distribution of the world's population and of the fall-out of ^{90}Sr and of ^{89}Sr. In order to compute doses to populations it is convenient to know the population-weighted deposition. These have been computed from the data in table 26 and are shown in table 27 for the northern and southern hemispheres.

183. *Strontium-89.* Since ^{89}Sr fall-out is a good indicator of the activity of other short-lived fission products, some deposition data are included in order to extrapolate external doses from the short-lived fission products. The latitudinal distribution of the integrated deposit of ^{89}Sr from 1961 to 1969 given in table 26 indicates that the general shape of the distribution in the northern hemisphere is much the same as that of ^{90}Sr (228). In table 27 are shown the global and the northern and southern hemispheric population-weighted estimates of deposition of ^{89}Sr. The annual deposition in each hemisphere from 1961 to 1969 is shown in table 28.

(ii) *Levels in food*

184. The annual ^{90}Sr activities of milk during 1966 through 1971 are shown in table 29. Average $^{90}Sr/Ca$ ratios in milk of the north temperate latitudes are given in table 30. The rapid reduction in activity observed between 1964 and 1967 has now ceased, there being only a small change in activity between 1968 and 1971. This probably reflects the fact that during the last few years the ^{90}Sr in milk is attributed largely to the cumulative deposit in soils which at present is changing only slowly with time (32, 51).

185. The $^{90}Sr/Ca$ ratios in total diet are shown in table 31 for the years 1966 through 1971. As with

milk, there has been little change in the levels between 1968 and 1971. The ratios of $^{90}Sr/Ca$ in total diet to that in milk are shown in table 32. Variations within individual countries are apparent, and even greater variations are noted between different countries, particularly between those with different diet types. As shown by Aarkrog (2) and Bennett (51), the relative contribution of ^{90}Sr from different components of the diet, milk, grain products, vegetables, meat, etc., has been changing with time. Changes in the diet-milk ratio are thus expected, particularly following changes in ^{90}Sr deposition, but the ratio should stabilize at later times. From the ratios given in table 32, it appears that an approximate mean constant diet-milk ratio of 1.4 will be an appropriate, useful relationship.

(iii) *Transfer from deposit to food*

186. A mathematical formalism to account for the transfer of deposited radio-activity to diet and the transfer from diet to the human body was developed in the Committee's 1969 report. The transfer coefficient from fall-out to diet is defined as

$$P_{23} = \frac{IC}{IF_r}, \tag{5}$$

where IC is the integrated level of the radio-nuclide in diet,

$$IC = \int_{-\infty}^{\infty} C(t)dt, \tag{6}$$

and IF_r is the integrated deposition of that radio-nuclide,

$$IF_r = \int_{-\infty}^{\infty} F_r(t)dt. \tag{7}$$

187. The activity in diet at time t, $C(t)$ can be related to the deposition at time τ, $F_r(\tau)$ by the relation

$$C(t) = \int_{-\infty}^{t} K(t,\tau)F_r(\tau)d\tau, \tag{8}$$

which serves to define the deposit-to-diet transfer function $K(t, \tau)$. In practice data are available on a monthly or annual basis so that the integral in (8) is replaced by a sum, so the activity in diet in year n is given by

$$C(n) = \sum_{i=-\infty}^{i=n} K(n,i)F_r(i) \tag{9}$$

where $F_r(i)$ is the deposition in year i. If it is assumed that the weighting function $K(n, i)$ only depends upon the elapsed time ($m = n-i$) since deposition, the integrated dietary level over infinite time is then,

$$\begin{aligned} IC &= \sum_{n=-\infty}^{\infty} C(n) = \sum_{n=-\infty}^{\infty} \sum_{i=-\infty}^{i=n} K(n-i)F_r(i) \\ &= \sum_{i=-\infty}^{\infty} \sum_{n=i}^{\infty} K(n-i)F_r(i) \\ &= \sum_{m=0}^{\infty} K(m) \sum_{i=-\infty}^{\infty} F_r(i) \\ &= IF_r \sum_{m=0}^{\infty} K(m). \end{aligned} \tag{10}$$

Thus the transfer coefficient P_{23} is given by

$$P_{23} = \sum_{m=0}^{\infty} K(m). \tag{11}$$

188. In the 1962, 1964 and 1966 reports of the Committee, the following form of transfer function $K(m)$ was used,

$$K(m) = p_r\,\delta_m + p_d \exp(-\lambda m) \tag{12}$$

where

$$\delta_m = 1,\ m = 0$$
$$\delta_m = 0,\ m \neq 0$$

Thus the level in diet during year n is

$$\begin{aligned} C(n) &= \sum_{m=0}^{\infty} p_r\delta_m F_r(n-m) + p_d F_r(n-m)\exp(-\lambda m) \\ &= p_r F_r(n) + p_d F_d(n) \end{aligned} \tag{13}$$

where λ is the physical decay constant of ^{90}Sr and $F_d(n)$ the cumulative deposition up to year n. This type of transfer function has been widely used to relate the ^{90}Sr activity in national milk supplies to deposition in previous years. Bartlett (32) found that equation 13 did not adequately fit the United Kingdom data and therefore proposed a relationship of the type

$$\begin{aligned} C(n) = p_1 F_r(n) &+ p_2 F_b(n-1) \\ &+ p_3 [F_a(n-1)\exp(-1.25\mu) \\ &+ \sum_{m=2}^{\infty} F_r(n-m)\exp(-\mu m)] \end{aligned} \tag{14}$$

where $F_a(n)$ and $F_b(n)$ are the deposition in the first and second half of year n, respectively, and μ is a decay constant which combines the physical decay of ^{90}Sr and any increasing unavailability of ^{90}Sr in the soil to plants, which is assumed to be exponential.

189. Since most of the food levels in the world have been reported on a calendar-year basis a relationship of the form

$$\begin{aligned} C(n) = p_1 F_r(n) &+ p_2 F_r(n-1) \\ &+ p_3 \sum_{m=2}^{\infty} F_r(n-m)\exp(-\mu m) \end{aligned} \tag{15}$$

can be used in an attempt to accommodate the effect of food storage from one year to the next.

190. In fitting by least squares the transfer functions of equations 14 and 15 to milk and deposit data, all the parameters p_1, p_2, p_3, and μ are allowed to vary. Bartlett (32) found that equation 14 gave an excellent fit to the United Kingdom data and obtained a shorter mean residence time in soil of 6.7 years. On the other hand, when both equations are fitted to the data of New York and Denmark, equation 15 gives a better fit. The average $^{90}Sr/Ca$ ratios in milk for the northern hemisphere have also been fitted to the fall-out data for the 30°-50° N latitude band using equation 15. The estimates of the parameters thus obtained, together with the value of P_{23} computed from equation 11, are shown in table 33. The values of μ obtained indicate that the effective mean life of ^{90}Sr in soil is between 7 and 10 years which is smaller than reported in earlier Committee reports; however, several more years of

data will be required to determine μ with greater confidence. The fits obtained with data from a number of areas and with the pooled data from the northern hemisphere are shown in figure XVIII.

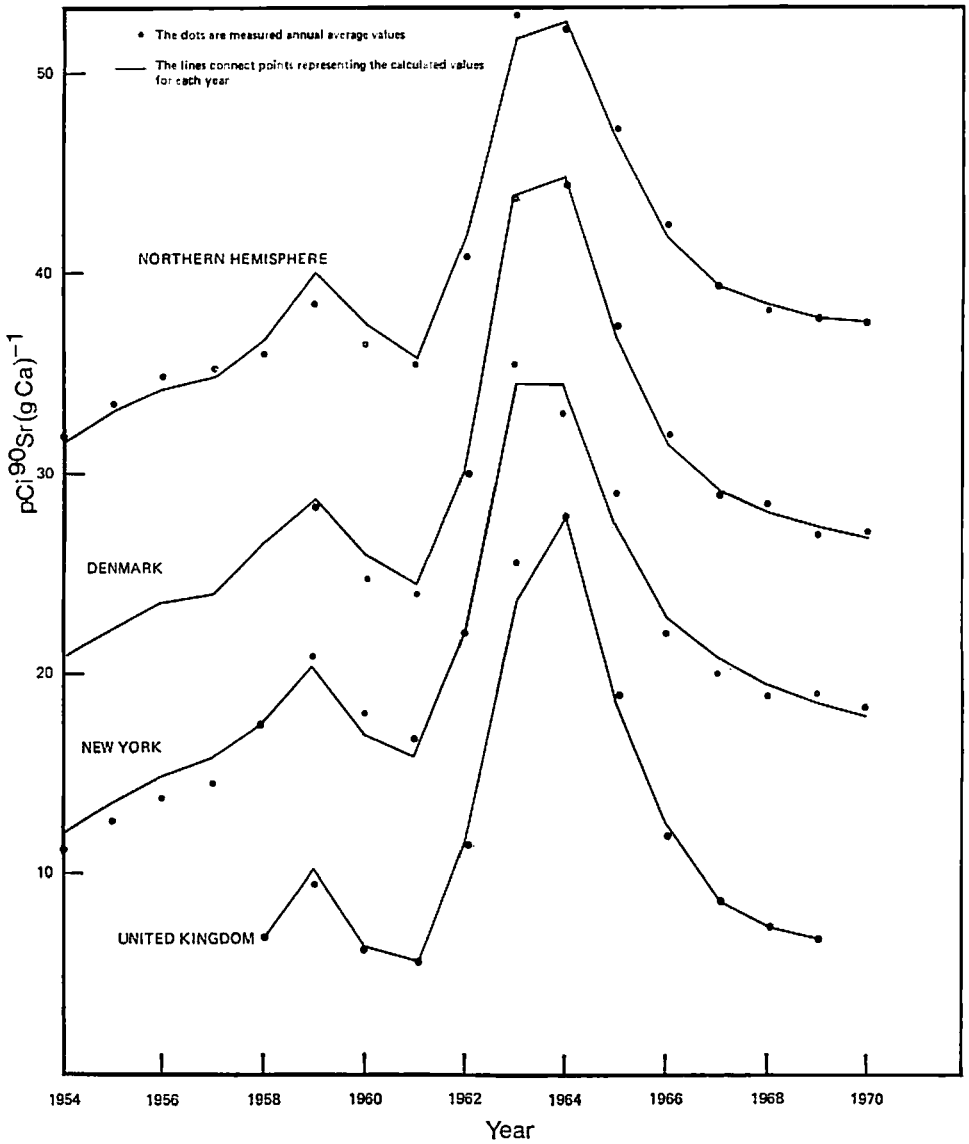


Figure XVIII. Measured and calculated annual average ^{90}Sr/Ca ratios in milk. The calculated results are based upon deposition data. Equation 15 was used for all results except for those of the United Kingdom for which equation 14 was applied. The curves for New York (USA), Denmark and the northern hemisphere are displaced upwards by 10, 20 and 30 divisions, respectively, for clarity

191. In 1970 the ^{90}Sr/Ca level in milk in the northern hemisphere was 7.4 pCi $(gCa)^{-1}$ and the corresponding integrated level 161 pCi y $(gCa)^{-1}$ (table 30). Assuming an effective mean life in the soil of 10 years (table 33, northern hemisphere) the estimated future integrated level in milk is 74 pCi y $(gCa)^{-1}$ giving a total integrated level in milk of 235 pCi y $(gCa)^{-1}$. With an integrated deposition (40-60° N) up to 1970 inclusive of 80 mCi km^{-2} (table 26) a value of 2.9 is obtained for the deposit-to-milk transfer coefficient P_{23} (milk). From table 33 we can assign a lower limit to the mean life in the soil of 5.5 years, while the upper limit is 40 years. Using these values one obtains lower and upper limits to P_{23} of 2.5 and 5.7. A value of 5 was used in the 1969 report of the Committee. In this report a value of 3.2 is taken (table 33) for the purposes of computing dose commitments. The deposit-to-diet transfer coefficient is obtained from the corresponding value for milk by multiplying by 1.4, resulting in P_{23}(diet) = 4.5 pCi y $(gCa)^{-1}$ per mCi km^{-2}. The value of this factor is based upon data from countries in northern temperate latitudes which have a western type diet. It may be different for other types of diet or in other geographical regions. However, since there are few data from other regions, the value of 4.5 will be assumed to apply globally, for the purposes of computing doses.

(iv) *Levels in bone*

192. New data on ^{90}Sr in bone are shown in table 34, including results from the limited bone-sampling programme undertaken by the World Health Organiza-

tion. A definite variation with age in the ^{90}Sr levels in bone appears up to the age of 20 years, values being higher between one and four years. The relative uniformity of levels in adult bone compared to the variability in deposition of ^{90}Sr must be noted and will be worth detailed consideration when samples from a few further areas are received by the WHO. Table 35 and figure XIX show the time trends of ^{90}Sr levels in

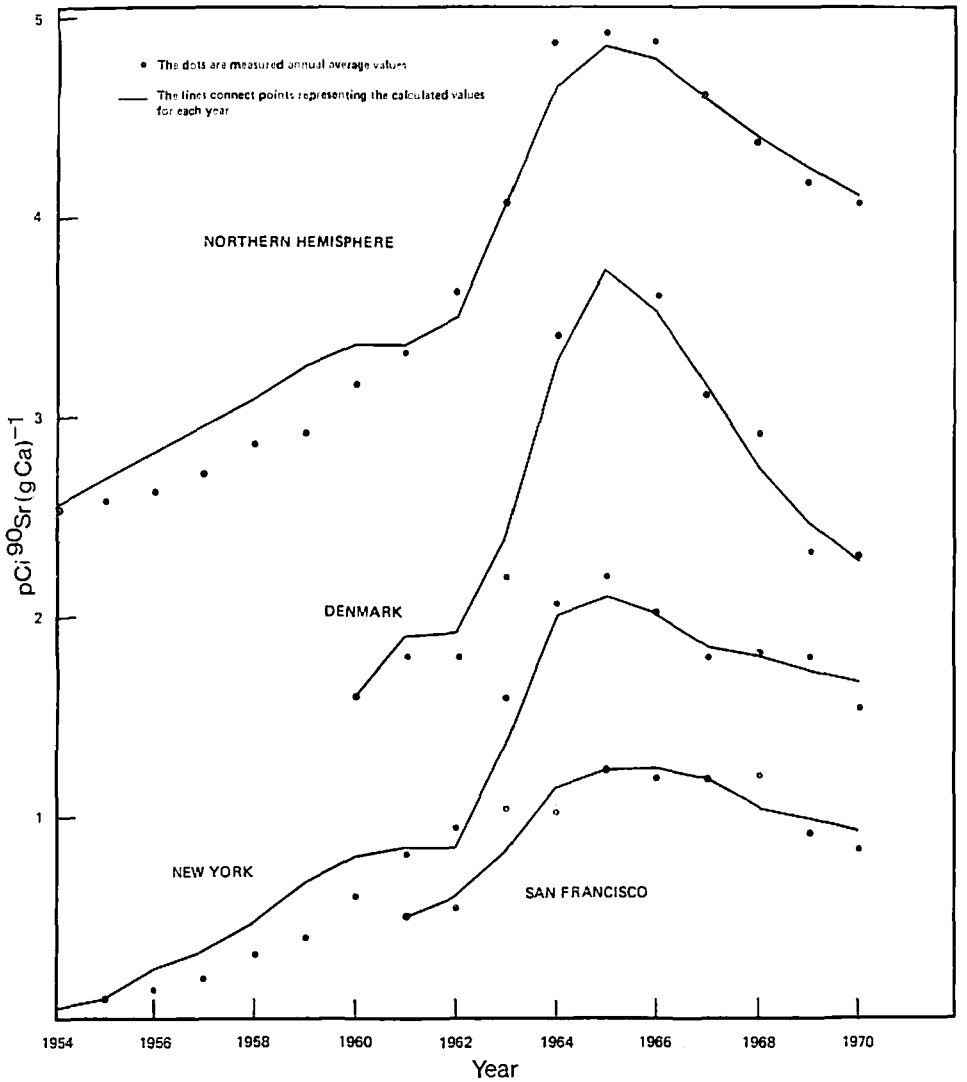


Figure XIX. Measured and calculated annual average $^{90}Sr/Ca$ ratios in human adult vertebræ. The calculated values were obtained using equations 26 and 30. For Denmark, New York and San Francisco, the activity of ^{90}Sr in bone was computed from that in total diet but for the northern hemisphere it was computed from the activity of ^{90}Sr in milk. For the sake of clarity the Danish and northern hemisphere results have been displaced upwards by 1 and 2.5 divisions, respectively

adult vertebræ in the northern hemisphere. In general levels have continued to decrease since 1965.

193. Beninson (46) has reported both stable strontium and ^{90}Sr measurements on the bones of a large number of persons whose age at death varied from 0 to 30 years. He found the ratio of stable strontium to calcium in bone to be fairly constant from 1 to 30 years. Much of the variation with age of the $^{90}Sr/Ca$ ratio in bone can be attributed to differences in turnover rate which, as has been shown by Beninson (46) and Bennett (50), varies significantly with age. This turnover rate is highest in infants under 1 year of age, falls to a minimum about age 4 years, then rises to a maximum at 8-10 years and then falls again, remaining constant above the age of 20 years.

194. The ratio of ^{90}Sr in vertebræ to that in femoral diaphyses has been determined for adults in Czechoslovakia, where the average value for 51 samples was 2.28 ± 0.22 in 1969 (77) compared with 2.68 ± 0.31 in 1968 (76). In Moscow the corresponding figures were 2.30 ± 0.06 and 2.38 ± 0.04 for 1968 and 1969, respectively (674). When these figures are compared with those reported in the 1969 report it is evident that the ratio has decreased considerably since 1965. In Czechoslovakia the 1969 ratio in males (2.36) appears to be significantly greater than in females (2.06) as was also the case in 1968.

(v) *Transfer from food to bone*

195. The transfer coefficient P_{34} is defined as

$$P_{34} = \frac{IQ}{IC} \tag{16}$$

where $IQ = \int_{-\infty}^{\infty} Q(t)dt$ and $IC = \int_{-\infty}^{\infty} C(t)dt$

where $C(t)$ is the average $^{90}Sr/Ca$ ratio in diet and $Q(t)$ is the population-weighted ^{90}Sr ratio in bone at time t.

196. In the Committee's earlier reports P_{34} was determined using a model developed by Lindell (363). In the 1969 report, P_{34} was estimated from observed levels in bone through the relation

$$P_{34} = (G_t + H_t)/C_t \tag{17}$$

where C_t is the integrated dietary level of ^{90}Sr up to time t,

$$C_t = \int_{-\infty}^{t} C(t')dt', \tag{18}$$

and G_t is the integrated level in human bone up to time t averaged over all age groups

$$G_t = \frac{1}{70}\int_{-\infty}^{t} \int_{0}^{70} S(t', u)du\, dt' \tag{19}$$

where $S(t', u)$ is the level in bone at time t' for a person of age u and 70 is the average life span expressed in years. The quantity H_t is the integrated future level in bone due to ^{90}Sr already deposited there, also averaged over all age groups, or

$$H_t = \frac{1}{70}\int_{0}^{70} S(t,u'')W(u'')du'' \tag{20}$$

where

$$W(u'') = \int_{u''}^{70} \frac{B(u'')}{B(u)} \exp[-k_1(u-u'')]du \tag{21}$$

where $B(u)$ is the mass of calcium in the skeleton at age u, k_1 is the turnover rate of ^{90}Sr in bone. $W(u'')$ is called the integral weighting function. In 1969 about 40 per cent of P_{34} was due to the H_t term. A value of 0.1 y^{-1} was used for k_1 in the 1969 report. Any uncertainty in k_1 will give rise to errors in the estimate of P_{34}.

197. If $Q(t, u)$ is the activity in bone in a cohort of the population whose age at time t is u, then

$$Q(t, u) = \int_{-\infty}^{t} C(\tau)m(t, \tau, u)d\tau, \tag{22}$$

this equation defines the transfer function $m(t, \tau, u)$ (616). If the transfer function depends only on the time ($v = t-\tau$) elapsed since dietary intake, then

$$\int_{-\infty}^{t} C(\tau)m(t, \tau, u)d\tau = \int_{0}^{\infty} C(t-v)m(v, u)dv$$

Assuming a steady population with $N(u)$ people of age u and

$$N = \int_{0}^{70} N(u)du,$$

the activity in bone averaged over all age groups is

$$\begin{aligned} Q(t) &= \frac{1}{N}\int_{0}^{70} du \int_{-\infty}^{t} N(u)C(t-v)m(v, u)d\tau \\ &= \int_{0}^{\infty} C(t-v)dv \frac{1}{N}\int_{0}^{70} N(u)m(v, u)du \\ &= \int_{0}^{\infty} C(t-v)K(v)dv \end{aligned} \tag{23}$$

Therefore $K(v)$ represents a population-weighted transfer function. Now,

$$\begin{aligned} IQ &= \int_{-\infty}^{\infty} Q(t)\ dt = \int_{-\infty}^{\infty} dt \int_{0}^{\infty} C(t-v)K(v)dv \\ &= \int_{0}^{\infty} K(v)dv \int_{-\infty}^{\infty} C(t)dt = IC\int_{0}^{\infty} K(v)dv \end{aligned} \tag{24}$$

so that

$$P_{34} = \int_{0}^{\infty} K(v)dv \tag{25}$$

198. In practice, because the dietary and bone data are available on an annual basis, the integrals in equations 23 and 25 are replaced by sums

$$Q(n) = \sum_{m=0}^{\infty} C(n-m)K(m), \tag{26}$$

$$P_{34} = \sum_{m=0}^{\infty} K(m) \tag{27}$$

where $Q(n)$ is the ^{90}Sr level in bone in year n and $C(m)$ is the dietary level in year m.

199. In attempting to fit the adult bone data with a simple equation, the following types of transfer functions were tested on the New York bone-diet strontium data:

(*a*) exponential	$g\exp(-\mu m)$	(28)
(*b*) double exponential	$c\exp(-\nu m) + g\exp(-\mu m)$	(29)
(*c*) rate term + exponential	$c\,\delta_m + g\exp(-\mu m)$	(30)
(*d*) power function exponential	$g(m+1)^{-b}\exp(-\mu m)$	(31)

The simple exponential function is equivalent to the model used by Rivera and Harley (530) for adult bone. The rate term + exponential is equivalent to the model used by Coulon and Madelmont (124) when applied to adult bone. According to Coulon and Madelmont, the rate term in their model accounts for that part of strontium in bone which is in rapid exchange with that in plasma. The power function exponential model has been found by Marshall *et al.* (401) to give good fits to bone ^{90}Sr levels after a single exposure.

200. All parameters c, g, b, ν and μ were allowed to vary in the least squares fit. The best fit was obtained

with the rate term plus exponential function and in fact the double-exponential reverted to this latter model since the value of ν obtained was greater than 12 y^{-1} and all the other parameters were the same. The parameters obtained by a least-square fit of the rate term + exponential model to the diet-bone data of New York, San Francisco, Denmark and the northern hemisphere are shown in table 36. Also shown in table 36 are parameters obtained from the British data, using an exponential model to fit the ^{90}Sr in vertebræ (478). The northern hemisphere diet data were obtained by multiplying the milk levels given in table 30 by 1.4. The fits obtained for these three sets of data are shown in figure XIX. Since the data for the northern hemisphere are of a composite nature, it is not surprising that the fit is not quite as good as for the New York and Danish data. It should be noted from table 36 that, although the estimates of the mean turnover rate in bone are different for the three sets of data, the values of P_{34} obtained are fairly constant. In general, if the uptake of strontium by bone is governed by linear processes, then it might be expected that the integrated level in bone would be fairly independent of the turnover rate.

201. The least-square fit is not very sensitive to changes in μ, so the differences in μ shown in table 36 may not be significant. Marshall *et al.* (401), from a study of the retention by cancellous bone after a single injection of strontium, estimate μ to be 0.10 y^{-1}.

202. It is also possible to estimate P_{34} from the bone and diet data directly, using equations 17 through 21, as was done in the 1969 report of the Committee. The limitation here is that the turnover rate k_1 in bone must be pre-specified. Estimates of P_{34} were calculated for the years 1965 through 1970 assuming three different values of k_1, notably 0.1, 0.3 and ∞. The data were taken from table XIII of annex A of the 1969 report and tables 30 and 35 of the present report. The milk levels were multiplied by 1.4 to estimate the total diet levels. The three estimates of P_{34} are plotted against $C(t)/C_t$ in figure XX. The estimates of P_{34} are approximately constant for a turnover rate of

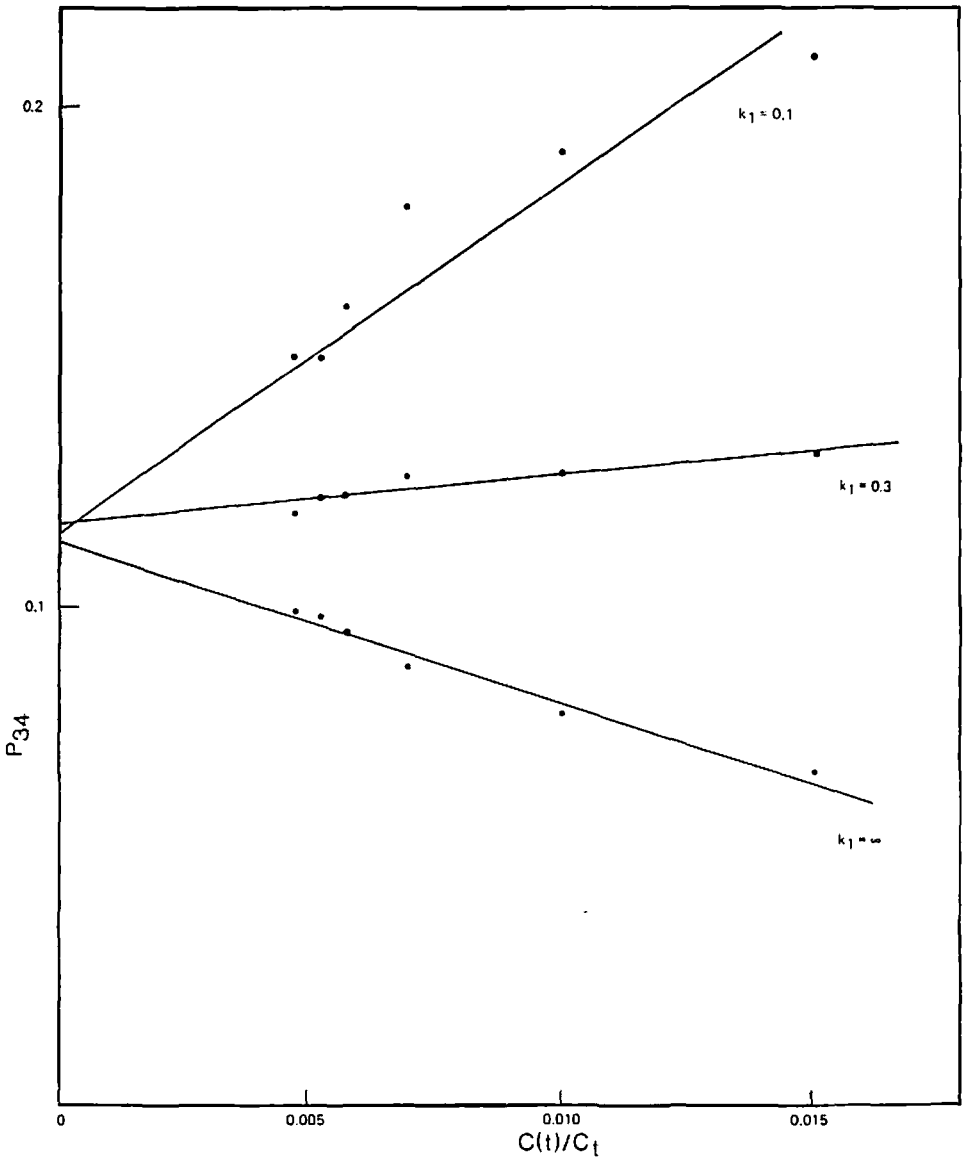


Figure XX. Values of P_{34} calculated from equation 17 assuming three different values of the turnover rate k_1 of strontium in bone. The $^{90}Sr/Ca$ ratios in human vertebræ and diet are for the northern hemisphere, 1965 to 1970

$k_1 = 0.3$ y^{-1}, indicating that this turnover rate is about correct for the data. If straight lines are drawn through the three sets of points, they intersect the $C(t)/C_t = 0$ axis at about $P_{34} = 0.12$.

203. Thus these estimates of both the turnover rate and P_{34} are in agreement with those in table 36 for the northern hemisphere data. A value of 0.12 will be taken for P_{34} to compute the dose commitment from ^{90}Sr.

204. A transfer function P_{34} for stable strontium can also be determined by the same rate term + exponential model (equation 30) as used for ^{90}Sr. Since there is no radio-active decay, μ must be reduced by 0.025. If this is done for the parameters of the New York and San Francisco data shown in table 36, stable strontium values of P_{34} for New York and San Francisco of 0.14 and 0.18, respectively, are obtained. Rivera (529) reported values of 0.16 and 0.16, respectively, based upon stable strontium measurements in bone and diet.

(vi) *Dose commitment from ^{90}Sr*

205. For the purpose of dose estimation, it was previously assumed by the Committee that ^{90}Sr is uniformly distributed in the seven kilogrammes skeleton of standard man (616). Committee II of the ICRP has recently qualified the skeletal mass to include five kilogrammes of bone mineral in addition to cartilage and peri-articular tissue (401). Assuming the ^{90}Sr to be uniformly distributed only in bone mineral has the effect of increasing D_o, the dose rate per unit activity to a small tissue-filled cavity in bone. D_o is given by Spiers (577)

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

where $N_m = 1.17\ 10^6\ M^{-1}$ y^{-1} per pCi (gCa)$^{-1}$ = number of beta particles emitted per picocurie of ^{90}Sr per gramme of calcium; $M = 5$, being the mass, in grammes, of mineral bone per gramme of calcium (401, 650); $\bar{E}$ = the effective energy of beta-rays emitted (1.13 MeV for ^{90}Sr + ^{90}Y); $(S_T/S_B)_m$ = the ratio of the mass stopping powers in tissue and bone = 1.07 (52); K_B and K_T = factors allowing for the effect of scattering on the effective particle range, assumed to be unity here (163). So that $D_o = (1.17\ 10^6\ 1.13\ 1.6\ 10^{-5}\ 1.07)/5 = 4.5$ mrad y^{-1} per pCi (gCa)$^{-1}$.

206. Spiers (580) has re-estimated the values of D_m/D_o and D_s/D_o where D_m and D_s are the dose rates in bone marrow and endosteal cells, respectively, per unit activity in bone. The new values are:

	D_m/D_o	D_s/D_o
Cortical contribution	0.055	0.082
Trabecular contribution	0.260	0.352
TOTAL	0.315	0.434

Using these values we obtain:

P_{45} (marrow) = 4.5 0.315 = 1.42 mrad per pCi y (gCa)$^{-1}$

P_{45} (endosteal cells) = 4.5 0.434 = 1.95 mrad per pCi y (gCa)$^{-1}$

The values used in the Committee's 1969 report were 0.55 for doses to marrow and 1.1 for doses to endosteal cells.

207. The following values of the transfer coefficients are used:

P_{23} (fall-out/diet) = 4.5 pCi y (gCa)$^{-1}$ per mCi km^{-2} (paragraph 191),

P_{34} (diet/vertebræ) = 0.12 pCi y (gCa)$^{-1}$ per pCi y (gCa)$^{-1}$ (paragraph 203),

P_{45} (bone marrow) = 1.42 mrad per pCi y (gCa)$^{-1}$ (paragraph 206),

P_{45} (endosteal cells) = 1.95 mrad per pCi y (gCa)$^{-1}$ (paragraph 206).

The deposition from ^{90}Sr from all tests to 1970 in the temperate zones is taken to be (tables 26 and 27)

Northern hemisphere ..... 80.3 (58.4)[5] mCi km^{-2}
Southern hemisphere ..... 22.1 (13.9) mCi km^{-2}

The resulting estimates of dose commitment are shown in table 37.

(f) *Iodine-131*

208. Eleven radio-active isotopes of iodine, most of them short-lived, originate in nuclear fission. Only ^{131}I, because of its half-life of eight days, is present in significant amount in the long-range tropospheric fall-out shortly after atmospheric nuclear detonations. Iodine-129 (half-life 1.6 10^7 years) is a negligible radiation hazard in fall-out as its activity is very low.

209. Iodine present in diet in soluble form is probably completely absorbed from the gastro-intestinal tract into the blood and is selectively concentrated in the thyroid gland. The stable iodine concentration in the thyroid tissue is of the order of 400 to 500 micrograms per gramme of tissue while in the rest of the body it is much less than one microgramme per gramme (577). The mass of the thyroid is of the order of 20 grammes in the adults and about 10 times less in 0–1-year-old babies (144, 430). Consequently, young children receive a higher dose than adults from a given intake of radio-iodine. The dose to the whole body is of the order of a thousandth of that to the thyroid (36).

(i) *Transfer to man*

210. Ingestion and inhalation are the two principal modes of entry of ^{131}I into the body. The transfer to man by ingestion is complex as it depends on a variety of factors including meteorological conditions, agricultural practices and biological variability.

211. Radio-active fall-out is observed to circle the earth in 20-30 days on average (527) which is approximately the mean residence time of an aerosol in the troposphere. It is unlikely that during such a short period the clouds of debris become well mixed. The surface-air concentration of ^{131}I at a particular station will fluctuate according to meteorological conditions and will not necessarily be representative of a larger region nor of a latitude band (486).

212. Information on the physical and chemical nature of fall-out ^{131}I is very limited. In the United Kingdom, late 1961, an average 75 per cent of the activity was in particulate form, the rest being in the gaseous state (152), but in the United States in 1962 the particulate fraction was found to vary from 10 to 90 per cent (500). These large variations are thought to be

[5] Figures in brackets refer to the whole hemispheres, the others to the northern and southern temperate zones (40°-60°).

due both to the origin of the fall-out and to the history of the air masses undergoing physical and chemical transformations during the travel.

213. Radio-iodine is deposited on the ground and on vegetation by dry and wet processes. The rate of dry deposition is characterized by the deposition velocity which, for ^{131}I fall-out, is of the order of 5 10^{-3} m s^{-1} (107). When precipitation occurs, ^{131}I is deposited at a much faster rate than in dry weather, essentially by rain-out, or in-cloud, mechanisms rather than by wash-out, or below-the-cloud, processes (614). For instance, during the period June-September 1970, owing to the frequent occurrence of rain in Cape Town, South Africa, the deposition-to-surface-air concentration ratio was an order of magnitude higher in that city than in Pretoria, where it rained only four days (624). On the other hand, rain will wash the surfaces of the leaves and thus remove some of the radio-iodine (156). Chamberlain and Chadwick (107) calculated that, from September to December 1961, only about half of the ^{131}I falling out in rain was retained on herbage. Other processes, such as mechanical disturbance and re-volatilization, enhance the decrease of grass contamination. Evidence from laboratory experiments and nuclear industry releases shows that the effective half-time of ^{131}I on herbage is 3-6 days, most estimates lying around 5 days (53). Unfortunately, the results of measurements of ^{131}I in world-wide fall-out cannot be used to test the foregoing estimates as quantitative observations are usually obscured by the rapidly changing pattern of fall-out (189).

214. Fresh milk is usually the main source of ^{131}I in food because of the concentration achieved by the grazing animal and the short storage period of milk. The extent to which ^{131}I is transferred from vegetation to milk varies widely depending mainly upon density of the herbage and on feeding practices. The animal may feed partly only, or not at all, on contaminated grass and the milk produced may be diluted with uncontaminated milk at a dairy. Garner and Russell (189) suggested that from laboratory experiments the maximum level in cow's milk from continuous grazing after a single deposition of 1 pCi m^{-2} might be 0.15 pCi l^{-1}, corresponding to an integrated level of 1.5 pCi d l^{-1} and mentioned that ^{131}I in tropospheric fall-out might be reduced in availability because of its physical form. This hypothesis seems to be confirmed by fall-out results from Argentina, where the relationship between integrated milk level and deposition is 0.23 pCi d l^{-1} per pCi m^{-2} and shows little variation from year to year (47). On the other hand, the transfer coefficient from deposition to diet for ewes and goats is probably much higher as a considerable fraction of their ^{131}I intake is secreted in milk (189).

215. Milk dominates as a source of ^{131}I ingestion in areas where it is a major dietary component, but vegetables are probably the main source of intake where little milk is consumed (657). However, only milk will be considered here because of its important world-wide contribution in the diet of infants. It should be noted that there are three sources of milk in infants' diet: human milk, fresh milk from animals such as goats and cows, and dried or evaporated milk. Only fresh milk of animal origin contributes ^{131}I to their diet to a significant extent. In the United States, infants of more than six months of age consume mainly this kind of milk and their daily milk intake from six months to two years is about 0.7 litre (150). This figure has been assumed to be representative of many areas of the world.

(ii) *Doses*

216. The Committee, in its 1964 report, estimated at 16.5 rads the dose to the thyroid of a baby of less than two years of age resulting from the ingestion of one microcurie of ^{131}I. Similar results can be found in recent publications. Morley and Bryant (435), using values of parameters revised by the United Kingdom Medical Research Council in 1968, obtained a value of 15.5 rads per microcurie for a six-month-old baby while, according to Neil and Robinson's data (457) the corresponding figure for a 6–11-month-old baby is 18.5 rads.

217. Adopting average values for the parameters discussed above (table 38), the dose from ^{131}I fall-out to the thyroid of infants can be estimated at 4.0 mrad per pCi d m^{-3}. The corresponding dose to adults should be at least an order of magnitude lower because their average milk consumption is much less (620) and the mass of their thyroid is approximately 10 times larger.

218. Inhalation is another possible mode of exposure which can only be predominant when deposition of ^{131}I does not result in the contamination of the diet. Assuming that the blood uptake after inhalation is 0.75 of the uptake from ingestion and that six cubic metres of air are inspired daily by an infant (86), an integrated air concentration of 1 pCi d m^{-3} would lead to a thyroid dose of about 0.07 millirad.

219. Because ^{131}I deposition patterns are unpredictable, doses can only be calculated if the local deposit and transfer coefficients are known or if milk levels are measured. 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 whose milk supply has been adequately monitored.

220. During the period from 1951-1958, the pattern of weapons testing was such that copious tropospheric fall-out was produced, but neither interest in ^{131}I nor the proper tools for measuring it existed at that time (156). Integrated milk levels, crudely derived from beta air concentrations, were estimated to be of the order of one microcurie day per litre in certain areas of Utah, United States in 1952, 1953 and 1957 (491). Milk contamination from atmospheric tests during the period 1961-1968 was examined by the Committee in its 1964, 1966 and 1969 reports. In the northern hemisphere, the highest levels in milk were observed in Alaska in 1962 (37,800 pCi d l^{-1}), while in the southern hemisphere, the highest values were reported in Argentina in 1966 (27,000 pCi d l^{-1}).

221. Integrated milk levels resulting from the atmospheric tests conducted in 1970 and 1971 in the southern hemisphere are presented in table 39. The milk contamination pattern was clearly different in the two years but the values obtained in the same location are in general smaller than in 1966. There has been no report of significant milk contamination arising from the atmospheric tests performed in the northern hemisphere from 1969 to 1971.

(g) *Caesium-137*

222. Caesium-137 produced by nuclear explosions in the atmosphere is transported to the earth's surface

without fractionation with respect to ^{90}Sr, as shown by the relative uniformity of the observed $^{137}Cs/^{90}Sr$ ratios in air and deposit, which lie around 1.6. Caesium-137 enters plants mainly through surface contamination and is absorbed readily in the human body where its biological half-life is about 100 days.

(i) *Transfer from deposit to diet*

223. The transfer from deposit to diet is normally characterized by high uptake during the first years after deposition and by a relatively small uptake subsequently. The main dietary sources of ^{137}Cs are milk, meat, vegetables and cereals. A large number of milk analyses from different countries have been reported (table 29). 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. Milk being locally produced in most areas of the world, its levels are representative of the contamination of the regional agricultural production.

224. In a given country, variations of an order of magnitude from one region to another are common. Low concentrations predominate in the temperate regions where caesium is fixed in the solid phases of the soil and milk levels are strongly dependent on the deposition rate of the same year and of the preceding year. In those regions, the annual ^{137}Cs concentrations were fairly stable from 1968 to 1971. On the other hand, high concentrations, explained by a significant uptake from soils low in potassium and high in organic content, are mainly dependent on the ^{137}Cs cumulative deposit (2, 655, 673). From 1968 to 1970, the milk levels in those regions decreased with a half-time of about five years. The highest reported levels in 1970 (620 pCi l^{-1} with a range 70-1,600 pCi l^{-1}) were found in some forest areas of the Byelorussian SSR, where an increased uptake of ^{137}Cs from the soil into plants was most common in areas of peaty bog and clayed podzolic sandy soils with a high water-table, high moisture content and low pH (673).

225. On a world-wide scale, high milk levels are predominantly found in the high latitudes of the northern hemisphere but tracer experiments indicate that uptake of ^{137}Cs from red, lateritic and alluvial soils common in the tropics and subtropics might also be considerably higher than uptake from the clay soils of temperate regions (182). Unfortunately, measurements in local food products or people in the tropics are scarce.

226. Yearly averages of ^{137}Cs dietary intakes in various countries, summarized in table 31, are not closely related to milk levels for various reasons. Widespread distribution of grain products and meat, which provide about half of the ^{137}Cs intake, tend to smooth out the local variations observed in milk contamination. Furthermore, the grain products are often stored and may thus be representative of an earlier fall-out situation. This also applies to meat when livestock is fed with grain products prior to marketing.

227. Levels in such dietary items as fish or mushrooms depend strongly upon cumulative deposition. In the case of fresh-water fish, the activity concentrations are inversely related to the potassium content of the water (334), so that the activity of fresh-water fish can be one hundred times that of ocean fish, with a maximum value of a few nanocuries per kilogramme in fresh-water fish (166, 213). In 1968, fish accounted for 7 per cent of the ^{137}Cs dietary intake in Denmark. Mushrooms were shown to concentrate very effectively ^{137}Cs from soils with a high organic content (211, 296). Typical levels are several tens of nanocuries per kilogramme so that a single meal of mushrooms may increase the normally incorporated ^{137}Cs content to a considerable degree. As a result of these factors, the relative contribution of the individual food-stuffs varies from year to year and levels in diet have decreased between 1968 and 1970.

228. In its 1969 report, the Committee estimated at 4.1 pCi y $(gK)^{-1}$ per mCi km^{-2} the transfer coefficient P_{23} from deposition to diet. This value has been confirmed by studies conducted in Denmark and in the Soviet Union. In Denmark (2), the influence of the soil uptake on the levels in diet was so small that reliable determinations of the soil factor have been impossible and the dietary intake was related to the annual deposition in the same year and in the two preceding years, yielding 4.1 pCi y $(gK)^{-1}$ per mCi km^{-2} as P_{23}.

229. In the Soviet Union, the territory has been divided in two zones according to the importance of the soil factor which, although much greater than in Denmark, has not been calculated precisely (684). Assuming that the daily intake of potassium is 3.8 grammes and that the half-residence time of ^{137}Cs in the soil is equal to its physical half-life, the coefficient P_{23} lies in the range 3.8-7.3 and the contribution of the soil uptake is from 40 to 180 per cent of that of the surface uptake. If no major series of atmospheric tests takes place in the next few years, the contribution of the soil uptake will probably be more precisely determined.

230. Exceptionally high values have been observed in caribou and reindeer meat which is the staple food of the populations living in arctic regions. Levels of ^{137}Cs in caribou and reindeer are high because the lichens, which are an important food for these animals during winter, effectively entrap a substantial proportion of the deposit falling on to them, and retain it with an apparent half-life of a few years due to grazing and leaching. Two other food chains participate in the accumulation of ^{137}Cs in man more effectively in those regions than in the middle latitudes: fresh water–fish–man and fresh water–plants–milk–man (519).

(ii) *Transfer from diet to body*

231. 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. About 10 per cent is eliminated with a biological half-time of about one day, and the remainder is excreted at a slower constant rate (577). The observed half-life in adults varies between less than 50 and more than 200 days. Even within a relatively homogeneous group, the variability in half-life is considerable. The half-life in children is shorter than in adults and is of the order of ten days for new-born infants. Based on published data, McCraw (410) gave the empirical equation $T\ ½$ (days) $= 12.8\ (u^{½} + \exp(-u))$ where u is age in years.

232. Table 40 and figure XXI present ^{137}Cs levels in man in several countries. The average body content of ^{137}Cs in a population at a given time varies with individual values of the biological half-life and with

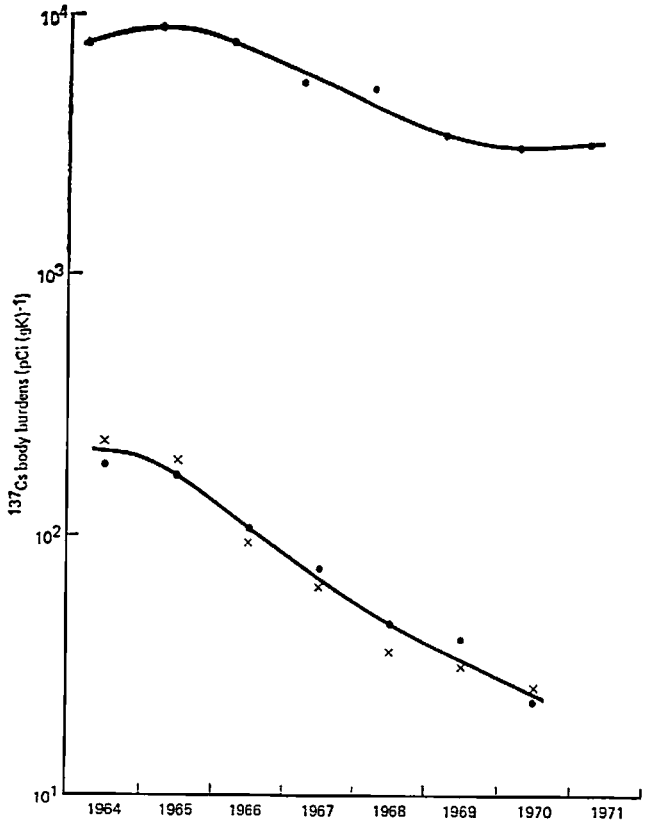


Figure XXI. ^{137}Cs body burdens (pCi (gK)$^{-1}$)

Upper curve: Inari male reindeer herders (Finland) (519-521)
Lower curve: Denmark (•) (5)
France (x) (490)

dietary habits. The variation with time of the average body burden of reference groups located in three cities of the Federal Republic of Germany shows three different slopes which probably reflect variations in the composition of the diet (92). The observed ^{137}Cs levels (in pCi (gK)$^{-1}$) are 20-30 per cent lower in women than in men. Levels in children are, in general, lower than in adults. However, in the areas of the Byelorussian SSR where high levels in milk were reported, the concentrations in children under 10 years of age were about the same as in adults (about 800 pCi (gK)$^{-1}$) as a result of their higher consumption of milk (673). For estimating the dose commitment, it will be assumed that the ^{137}Cs level (in pCi (gK)$^{-1}$) in children is the same as in adults, an assumption which probably leads to a small over-estimate of the population average.

233. Levels in subarctic populations are two orders of magnitude higher than in the middle latitudes. The highest values have been found in a small group of Lapps in the Murmansk region of the Soviet Union (679). For reindeer herders in Finnish Lapland, about 70-90 per cent of the total amount in the body comes from reindeer meat, about 5-15 per cent from cow's milk, and about 5-20 per cent from fish (519).

234. The short residence time of caesium in the human body implies that the ratio between integrated body content and total dietary intake over a few years will be a good estimate of the transfer coefficient P_{34}. The available data (tables 31 and 40) for the period 1968-1970 for diet and body content expressed in pCi (gK)$^{-1}$ yield an average of 2.9 which is the value adopted by the Committee in its 1969 report. As recent values of P_{23} and P_{34} are consistent with the figures given in the 1969 report, there is no need to change the value of P_{234} which will be taken as 11 pCi y (gK)$^{-1}$ per mCi km^{-2}.

235. However, there has been some indication that a small part of caesium might be fixed in bone with long residence time and this would increase the value of P_{34}. Both in Denmark and in the Soviet Union, the long-term component is much higher in the equation of transfer from deposit to man than from deposit to diet suggesting that a fraction of the body burden has a long residence time (2, 684). However, the Danish data from 1969 to 1971 seem to be less in agreement with the model and a significant trend is not apparent in the relative variations of ^{137}Cs in diet and man in the other countries during the period 1968-1970. If in the future the studies from Denmark and the Soviet Union prove to be representative of the situation in the other countries as well, then the upper limit for P_{234} would be about 25 pCi y (gK)$^{-1}$ per mCi km^{-2}.

(iii) *Dose commitments*

236. If the ^{137}Cs body content is expressed as pCi (gK)$^{-1}$, the dose-rate factor is approximately independent of age. It will be assumed as in the 1969 report that $P_{45} = 18$ μrad per pCi y (gK)$^{-1}$ which, combined with the estimate of $P_{234} = 11$ pCi y (gK)$^{-1}$ per mCi km^{-2}, gives $P_{2345} = 0.20$ mrad per mCi km^{-2}.

237. The average integrated deposits of ^{137}Cs in the north and south temperate latitudes, obtained by multiplying the ^{90}Sr values by 1.6, are 128 and 35 mCi km^{-2}, respectively. The corresponding dose commitments are 26 and 7 millirads. The upper limits, calculated from the studies conducted in Denmark (2) and in the Soviet Union (684) are about twice those values. An extensive study taking into account the variations in the demographic structure of the population and in the dose-rate factor as a function of age yielded a dose commitment for the Soviet Union of 19 millirads for all atmospheric tests before 1963 (687). This result is in good agreement with the above estimate for the north temperate latitudes from all tests before 1970. If the dose commitments are calculated from the population-weighted deposition of ^{90}Sr over the whole hemispheres, the results are 19 millirads for the northern hemisphere and 4 millirads in the southern hemisphere.

238. In the arctic and subarctic regions where people include reindeer and caribou meat in their diets, the dose commitment is much higher. In Finnish Lapland, the body burdens were estimated to decrease with an effective half-time of about four years from 1967 to 1969 leading to a dose commitment of approximately one rad (521). In different arctic regions of the USSR the dose commitment for the native population varies from 0.45 to 1.7 rads (677). A value of one rad is probably representative of other arctic regions. As those populations constitute a small fraction of the world's population, the enhanced doses that they receive do not contribute significantly to the world-wide dose commitment.

239. The external dose commitments from ^{137}Cs deposited on the ground are discussed in paragraphs 261-264.

(h) *Plutonium*

(i) *Levels in the environment*

240. Plutonium is a fissile element that has received the greatest attention as a possible source of biological hazard mainly in occupational work. It enters plants from the soil only to a very small extent (539) and less than one thousandth of that ingested in diet is absorbed through the gastro-intestinal tract, but when inhaled it is one of the most toxic of radio-active materials (145, 408). In recent years, the plutonium content of surface air has therefore been carefully monitored.

241. Plutonium-239, an alpha emitter with a physical half-life of 24,000 years, is a man-made radionuclide produced by neutron irradiation of ^{238}U. As a component of global fall-out, it is found in surface air (138, 140, 342, 471, 633, 686) (figure XXII)

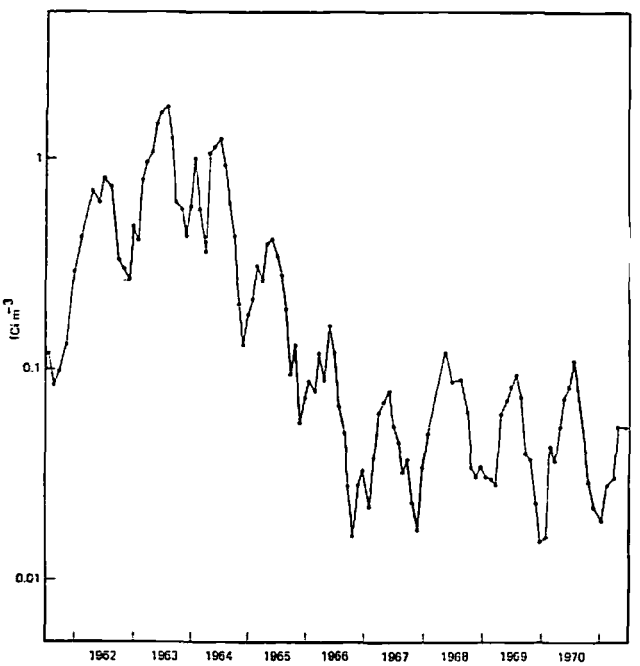


Figure XXII. ^{239}Pu concentration in surface air at Ispra, Italy (120, 133, 140)

where it is accompanied by smaller quantities of ^{240}Pu, from which it cannot be distinguished by alpha spectrometry (558), of ^{238}Pu in the ratio of 0.02 to 0.04 (1, 140, 344, 428) and of ^{241}Pu.

242. The total amount of ^{239}Pu produced in nuclear tests can be inferred from the ^{90}Sr corresponding value, since the $^{239}Pu/^{90}Sr$ activity ratio is about 0.02 both in stratospheric and in surface air (3, 235, 428, 429, 630). If the local fall-out is not taken into account, the production of ^{90}Sr by nuclear tests amounted to 15.5 megacuries in January 1971 (table 24) and the corresponding value for ^{239}Pu was 0.3 megacurie.

243. Appreciable amounts of ^{239}Pu were released locally to the environment when airplanes carrying nuclear bombs crashed in the vicinity of Palomares, Spain, in January 1966 and of Thule, Greenland, in January 1968 (3, 272). Near Palomares, the nuclear fuel of two thermonuclear weapons was burned out and an area of about two square kilometres was contaminated with plutonium and uranium particles. Contaminated vegetation and the top five centimetres of soils in areas with alpha-emitting levels above 320 pCi m^{-2} (about 8 per cent of the total contaminated area) were removed and stored as radio-active wastes. The rest of the area was plowed over down to a depth of about 25 centimetres, so as to dilute the concentration of radio-active elements in the soil. However, the combined action of dry climate, high wind velocities and farming of the soil have resulted on a few occasions in a significant resuspension of particles of plutonium oxides. A station located in a farming area recorded in 1967 a yearly average air concentration of 12 fCi m^{-3}, that is two orders of magnitude higher than the fall-out level (273).

244. Near Thule, the high-explosive components of four weapons detonated and resulted in contamination of about 0.2 square kilometre. An amount of about 200 curies was recovered in the surface layer of the snow pack and about 20 curies were estimated to be trapped in the ice (353). A radio-ecological investigation conducted during the summer of 1968, when the ice had broken up, showed that the plutonium levels in the collected samples in no instances were such that they could be considered harmful to man or to higher animals in the Thule district or in any other part of Greenland. Nevertheless, the accident measurably raised the plutonium level in the marine environment as far out as approximately 20 kilometres from the point of impact. The highest concentrations were found in bottom sediments, in bivalves and in crustacea. Larger animals such as birds, seals and walruses showed plutonium levels hardly different from the fall-out background (1, 3).

245. The amount of ^{238}Pu produced by nuclear tests can be estimated at about 10 kilocuries, if the $^{238}Pu/^{239}Pu$ and the $^{239}Pu/^{90}Sr$ ratios are assumed to be 0.03 and 0.02, respectively. An additional quantity of 17 kilocuries was injected into the stratosphere as a result of the burning on re-entry of a satellite that used this nuclide as a power source (233). Figure XXIII shows the changes of the $^{238}Pu/^{239}Pu$ activity ratio in surface air that followed that event (636). In November 1970, about 0.9 kilocurie, that is only 5 per cent of the original burden, remained in the stratosphere; the residence half-time of the total stratospheric inventory was 14 months during the period 1967-1970 (329).

246. A similar device re-entered the atmosphere and fell into the Pacific Ocean in April 1970. Another generator fell into the waters off the coast of California in May 1968 when a weather satellite exploded during launching. It was recovered in October 1968 (236).

(ii) *Doses*

247. The report of the Task Group on lung dynamics (268) of Committee II of the ICRP presents models of the deposition of particulate material in, and clearance of this material from, the respiratory tract. For a highly retained dust, such as plutonium dioxide, slow removal processes from the pulmonary region by direct translocation to the blood or by ciliary-mucous transport to the gastro-intestinal tract take place with a half-time of 360 days. Of this, 10 per cent is introduced into the systemic blood (half-time 360 days) and 90 per cent is presumed to be permanently retained in the lymph nodes.

248. Using these values, Voilleque (628) computed the doses to various tissues resulting from the inhala-

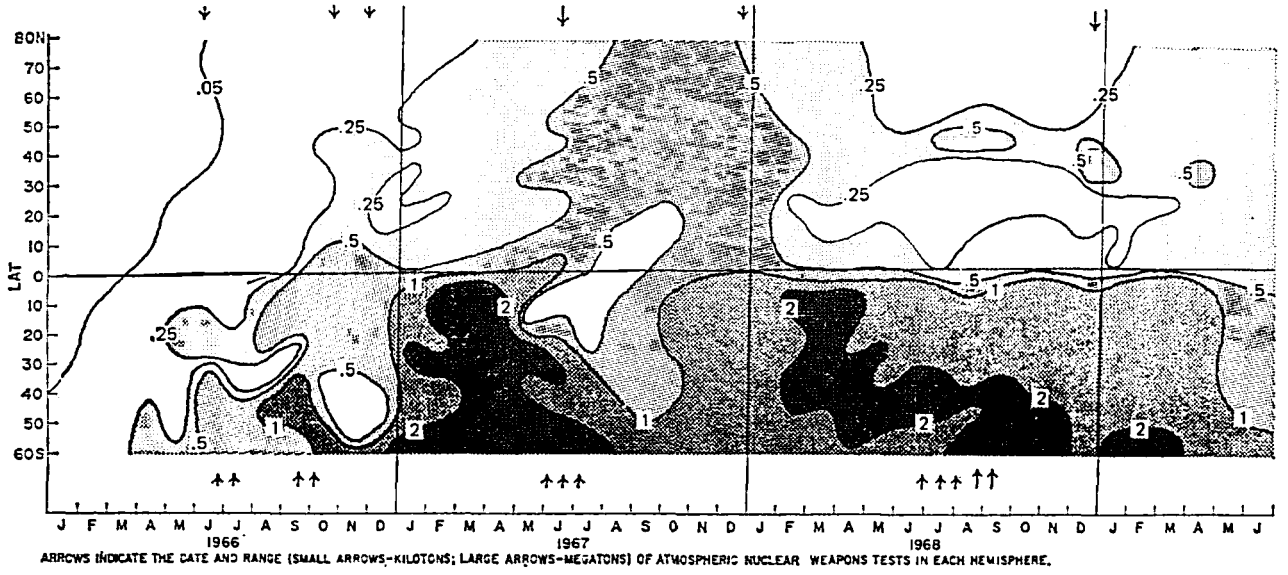


Figure XXIII. $^{238}Pu/^{239}Pu$ ratio in surface air (631)

tion of one microcurie of PuO_2 for the three mean particle sizes shown in table 41, which cover the range found experimentally. According to his calculations, the integrated doses over 50 years, corresponding to the inhalation for one year of air containing 1 fCi m^{-3} of $^{239}PuO_2$ distributed on aerosols of 0.5 micrometre AMAD,[6] are 0.43, 96, 0.20 and 0.04 millirad to the pulmonary region, the lymph nodes, the liver and bone, respectively.

249. Integrating the curve shown in figure XXII by adding the average annual concentrations for the period 1962-1970 gives an integrated level 2.6 fCi y m^{-3}. From the ^{90}Sr annual deposition values (table 24), the integrated level prior to 1962 can be estimated at 1.5 fCi y m^{-3}. The total integrated level from the beginning of the nuclear tests through 1970 would thus be of the order of 4 fCi y m^{-3}, which corresponds to integrated doses over 50 years of about 2, 400, 0.8 and 0.2 millirads to the organs and tissues cited above. It should be noted that the ICRP does not consider the lymphoid tissues to be critical in irradiation resulting from inhalation because experimental evidence has shown pulmonary rather than lymphatic tissue to be at risk (575).

250. The few measurements of ^{239}Pu in man (table 42) confirm the accumulation in respiratory lymph nodes, lung, liver and bone but seem to show that the concentrations in lymph nodes are probably overestimated whereas those in liver are underestimated. Results of analyses of tissue aliquots from a plutonium process operator who had been exposed for six years to ^{239}Pu largely *via* chronic low-level inhalation in an approximately known way have been published (180). The assumption that 90 per cent of the plutonium which reaches the lymph nodes is retained permanently leads in that case to an over-estimation by a factor of 13 of the concentration in those tissues relatively to that in the lungs. The correct value is obtained assuming a residence half-time of about two years. However, this result is based on only one individual. It is to be hoped that the National Plutonium Registry (137) established in the United States will contribute to the verification of the values of the parameters given by the Task Group on lung dynamics.

3. *External irradiation*

251. Several of the artificial radio-nuclides that are present in fall-out emit gamma rays and thereby give rise to an external radiation dose. In addition to various short-lived radio-nuclides, the most important of which are ^{95}Zr—^{95}Nb, the main contributor to external gamma radiation is ^{137}Cs which has a mean life of 43 years.

252. In principle it should be possible to calculate the external doses from the short-lived radio-nuclides using the deposition data for each nuclide and appropriate dose-rate conversion factors. Gustafson and Brar (215) determined dose-rate conversion factors for a plane distribution of fission products on the ground. More recently, Beck (37) and Beck and de Planque (38) have calculated dose-rate conversion factors, both for natural emitters and for fission products, using gamma-ray transport theory. These were computed both for plane and exponentially-distributed sources. Dose-rate factors based upon these calculations are shown in table 43. For ^{137}Cs the distribution is assumed to be exponential with a mean depth in the soil of three centimetres. For the short-lived fission products a plane distribution is assumed.

253. For the short-lived fission products, there is little leaching into the soil before they decay, but for ^{137}Cs, Gale *et al.* (187) found there was a rapid movement into the soil during the first few years and henceforth the distribution remained fairly static. The amount of penetration depended upon the soil type, but in all cases most of the ^{137}Cs remained in the top 10 centimetres of soil. The dose rate in air from ^{137}Cs was found to fit the following expression, where $D(t)$ is the dose rate in air in mrad y^{-1} per mCi km^{-2} of ^{137}Cs deposited:

$$D(t) = 0.12\,[0.63 \exp(-1.15t) + 0.37 \exp(-0.03t)] \qquad (32)$$

[6] AMAD = Activity Median Aerodynamic Diameter. The aerodynamic diameter is the diameter of a unit density sphere with the same settling velocity as the particle in question (268).

254. It is debatable whether, to allow for weathering, it is preferable to use a fixed exponential distribution in the soil or a dose rate that changes exponentially with time. There may also be some reduction in the gamma dose rate due to roughness of the terrain. In any case, large sections of the population live within paved cities, where a large fraction of the fission products would run off into the drainage system. Therefore, dose commitments calculated using the above models would probably give an upper limit.

(a) *Dose commitment from short-lived fission products*

255. In order to compute the dose commitment from the short-lived fission products it would be necessary to know the integrated deposition of each from 1950 until 1970. Although some data are available on the deposition of these fission products, they do not cover a long enough period to make an accurate estimate of the dose commitment possible. As in the previous Committee reports, we will rely on direct measurements.

256. The external dose in air from fission products in Tokyo, measured at one metre above a paved surface between 1958 and 1967 was 121 millirads (445, 446, 658). Between 1962 and 1967, the dose one metre above a grassed plot in Chiba City, Japan, was 122 millirads (445, 446).

257. Gibson *et al.* (195) have reported results on the gamma radiation from deposited fall-out at Grove, United Kingdom, for the period 1951-1967. These results, which are shown in figure XXIV, are based

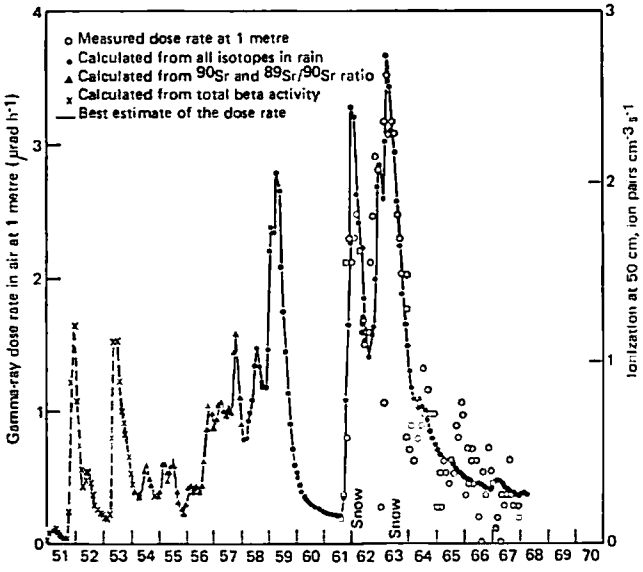


Figure XXIV. Gamma-radiation from deposited fall-out at Grove, UK, from 1951 to 1968 (195)

upon direct measurement and on calculation from deposition data. There was excellent agreement between the computed and measured dose rate. In 1967, the dose rate had fallen to about 15 per cent of that prevailing in 1962-1964. The annual dose from fission-product gamma rays reached a peak of 22.7 millirads in 1963, and for the period 1951-1967 the integrated dose was 131 millirads, of which 16 millirads were estimated to be from ^{137}Cs. Of the 1967 annual dose of 3.5 millirads, about 2.5 millirads were from ^{137}Cs.

258. At Grove, United Kingdom, the dose delivered between 1951 and 1967 from short-lived fission products deposited in the same period was 131 — 16 = 115 millirads, and if the small contribution to be delivered after this time is neglected, we can consider 115 millirads as the dose commitment.

259. In order to compute the population-weighted dose commitment for the northern hemisphere, we use the ^{90}Sr deposition up to 1967 at Abingdon (near Grove) of 43.2 mCi km^{-2} compared with the population-weighted mean for the northern hemisphere for the same period, 54.2 mCi km^{-2}. The dose commitment for deposition up to the end of 1967 is 115 (54.2/43.2) = 144 millirads. From table 28, it can be seen that in the northern hemisphere 1.3 megacuries of ^{89}Sr deposited in 1968-1969 compared with 51.7 megacuries in the period 1961-1967. Using this as a guide, the contribution to the dose commitment from deposition in 1968-1969 is at most 2.5 per cent. Adding this to 144 millirads, we obtain 148 millirads for the population-weighted dose commitment in the northern hemisphere for all deposition up to 1969. In the same manner, the dose commitment in the northern temperate latitudes (40°-60°) is estimated to be 203 millirads.

260. To estimate the dose commitment for the southern hemisphere, we use the deposition of ^{89}Sr in the northern and southern hemispheres for the period 1961-1969 (table 27), 260 and 71 mCi km^{-2}, respectively, as a guide, and assume the dose commitment to be proportional to these. The dose commitment in the southern hemisphere from short-lived fission products is thus 148 (71/260) = 40 millirads. In the temperate regions it is 60 millirads.

(b) *Dose commitment from ^{137}Cs*

261. Using 93.4 and 22.2 mCi km^{-2} as the total population-weighted deposition of ^{137}Cs in the northern and southern hemispheres, respectively, together with the dose-commitment conversion factor of 1.44 mrad per mCi km^{-2} from table 43, the dose commitments in the northern and southern hemispheres are 134 and 32 millirads, respectively.

262. It is possible to estimate the dose commitment from ^{137}Cs by another method. At Grove, United Kingdom, the dose from ^{137}Cs up to 1967 was 16 millirads and in 1967 the annual dose was 2.5 millirads (see paragraph 257). Assuming that the ^{137}Cs was already permanently distributed in depth within the soil, only the second term of equation 32, which has an effective mean life of 33 years, applies. Thus, the dose commitment at Grove for ^{137}Cs deposited up to 1967 is $16 + (2.5 \times 33) = 99$ millirads. Using the ^{90}Sr deposition at Abingdon up to 1967 of 43.2 mCi km^{-2} and the population-weighted deposition in the northern hemisphere of 58.4 mCi km^{-2} from all tests to 1970, the dose commitment for the northern hemisphere is 134 millirads, in agreement with the estimate made in the last paragraph.

263. To estimate average doses to the population it is necessary to consider the shielding afforded by buildings. A reduction factor of 0.2 will be taken as a world average for shielding by buildings (613). Also assuming an average time of 17 hours is spent indoors, the over-all reduction of dose due to shielding is 0.4.

264. In addition, in order to obtain the gonad and bone-marrow tissue doses, we must multiply by the (tissue/air) conversion factor of 0.8 discussed in paragraph 143. This factor allows for conversion from air dose to tissue dose in addition to screening by intervening body tissues. The combined factor to convert air doses to gonad and bone doses is thus 0.32. The dose commitments resulting from short-lived radionuclides and from ^{137}Cs for all tests up to the end of 1970 are shown in table 44.

4. *Summary of dose commitments*

265. Estimates of dose commitments from nuclear tests carried out before 1971 are summarized in table 45. For comparison, the estimates given in the 1969 report for tests conducted before 1968 are also included. Although no major series of tests occurred during the period 1968-1970, there are significant differences between the two sets of estimates for the internal dose commitments from ^{90}Sr to the bone-lining cells and for the external dose commitments to all tissues. As a result, the ratios of the external to the internal dose commitments for all tissues are found to be markedly higher in this report than in the 1969 report. Most of the changes are a consequence of improved information becoming available.

266. In the case of ^{90}Sr, the transfer coefficient from deposit to diet has been estimated as 4.5 pCi y $(gCa)^{-1}$ per mCi km^{-2} instead of 9 pCi y $(gCa)^{-1}$ per mCi km^{-2}, and the transfer coefficient from diet to vertebræ has been taken as 0.12 instead of 0.2. A reassessment of the dose-rate factors (P_{45}) resulted in changes from 1.1 to 1.95 mrad per pCi y $(gCa)^{-1}$ for bone-lining cells and from 0.55 to 1.42 mrad per pCi y $(gCa)^{-1}$ for bone marrow.

267. Estimates of doses from external radiation are higher, mainly because the ratio of the tissue dose to outdoor air dose is now taken as 0.32 instead of 0.2. However, the ^{137}Cs dose-rate factor used in this report is 0.033 mrad y^{-1} per mCi km^{-2} compared with 0.04 mrad y^{-1} per mCi km^{-2} used in the 1969 report. In addition, a small difference results from an incorrect use in the 1969 report of the cumulative rather than the integrated ^{90}Sr deposit to estimate the ^{137}Cs deposit. Doses from short-lived radio-nuclides have been estimated from actual measurements and the new tissue/air dose conversion factor was applied.

268. As a result of the combination of higher dose commitments from external radiation and lower dose commitments from ^{90}Sr, the relative importance of ^{90}Sr has decreased and ^{137}Cs appears to be the main contributor to the total dose commitment.

B. Underground and cratering explosions

269. During the last decades, in addition to the development of nuclear devices for military purposes, there has been an increasing interest in the peaceful applications of nuclear explosions. The inherent advantage of using nuclear explosives for peaceful applications lies in the huge energy source available in a small package at a relatively low cost per unit of energy released.

270. There are two basic types of explosions: *cratering explosions* in which nuclear explosives are potentially useful as an earth-breaking and moving tool for, e.g., uncovering of mineral deposits, canal construction, construction of earth and rock-fill dams, reservoir construction, creation of cuts and embankments for railways and roads, harbour construction, creation of craters for the disposal of mining and processing wastes; *contained explosions* in which the devices are potentially useful to break up or increase the permeability of the underground resource strata so that the resource can be recovered and used by man or to provide storage cavities. Examples are intensified exploitation of oil and natural gas deposits, stimulation of geothermal heat, creation of underground cavities for the storage of natural gas, gas condensates and oil products, creation of underground cavities for the burial of biologically dangerous industrial wastes, underground working of ore deposits, and stopping oil and gas blow-outs.

271. Both types of explosions present certain hazards. This report is only concerned with those arising from radiation exposure which may occur through (a) *release of radio-activity to the environment.* This is a primary concern with cratering exposions where some radio-activity is unavoidably released, but it is also relevant to contained explosions where the probability of accidental venting exists and where contamination of ground-water may occur. Of special concern are such nuclides as ^{3}H, ^{14}C, and ^{85}Kr because of their long half-life and high mobility in the environment; and (b) *the use of products recovered from "contained type" of explosions.* When nuclear energy is used to increase the availability of oil, natural gas, etc., the resulting products will be contaminated to some extent with radio-nuclides. These products could be used at locations far removed from the explosion.

1. *Sources of radio-activity*

272. There are two sources of radio-activity from a nuclear explosion, the direct products of the nuclear reactions (the fission fragments and tritium) and the radio-active products which result from activation of the surrounding medium (both inside and outside the explosive device).

273. The two design extremes are the pure fission device producing about 2.9 10^{23} fission fragments per kiloton and the pure fusion device which would produce no fission products but approximately from 10^{23} to 10^{24} atoms of ^{3}H per kiloton (depending on the efficiency and kind of thermonuclear fuel) (606). The excess neutrons produced (about 2 10^{23} neutrons per kiloton escape both from an unshielded fission explosive and from a fusion explosive) are captured either in the device or in its immediate environment (358). In this way, a variety of induced radio-active products are formed.

274. A fully contained one-megaton explosion (10 kt fission) surrounded by borated material would, if exploded in a medium with the average chemical composition of the earth's crust, produce radio-nuclides in the amounts shown in table 46 (583). The relative activities of the total fission products and the induced activities at various times after the explosion are shown in figure XXV. After one year the activity is entirely dominated by ^{3}H, ^{60}Co, ^{90}Sr and ^{137}Cs, tritium being the most abundant nuclide. After 10 years, tritium is still the most abundant nuclide and its activity is three orders of magnitude greater than that of ^{60}Co or ^{90}Sr.

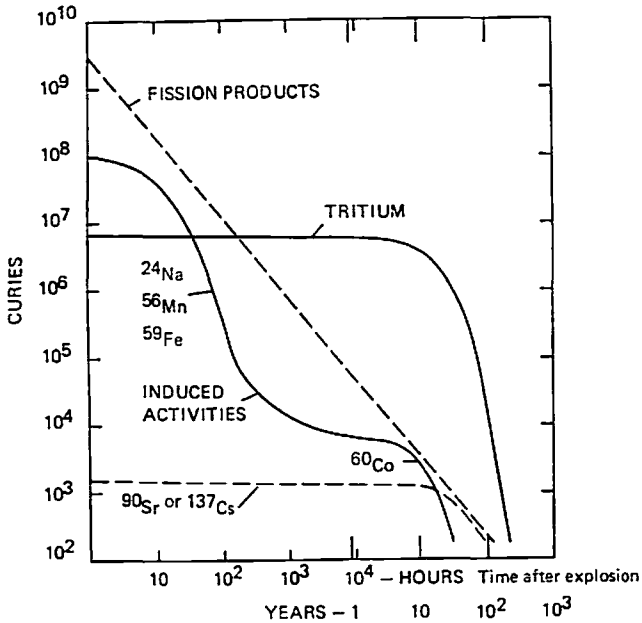


Figure XXV. Activities of radio-nuclides at various times after a nominal one-megaton explosion (10 kton fission) in average crustal material (583)

For peaceful applications, the explosive can be selected so as to minimize the potential hazard of the associated radio-activity.

275. For cratering explosions, Kelly (322), based on past experience, assumes that largely because of (*a*) the amount of scavenging during the venting process: (*b*) the effect of special emplacement techniques: and (*c*) the use of low fission explosives, the sum of fission products airborne in the radio-active cloud and in the fall-out for each nuclear explosive detonated may be expected to be as low as the equivalent of 20 tons. Further, the tritium release may be less than 20 kilocuries per kiloton of total yield. The inventory of selected products expected in the radio-active cloud and in the fall-out are shown in table 47.

276. For underground engineering, fission products (except ^{85}Kr) do not generally appear to be troublesome, but tritium, either from the explosive or from neutron reactions with trace lithium in the soil, gives rise to potential difficulties. Where hydrocarbons are involved, approximately 3 per cent of all neutrons that escape into the soil will produce tritium in typical shales (209). In addition, tritium might be produced in second-order reactions if boron is used as shielding material. Thus, a fission explosive with no neutrons allowed to leak to the soil should be used for hydrocarbon applications (209).

2. *Contained experiments*

277. The initial result of an underground nuclear explosion is the release of all its energy and of a large number of neutrons within less than a microsecond (463). The neutrons are thermalized and captured in the surrounding material, producing a variety of induced nuclides. The extreme pressures and temperatures ($> 10^6$ atmospheres and $> 10^7$ degrees) that are generated vaporize some of the surrounding material and give rise to a strong shock wave that propagates outwards. Initially this shock wave is sufficiently intense to vaporize additional rock and add its mass and volume to the cavity formed. In contained explosions the cavity reaches its peak size in a few hundredths (or tenths) of a second (667). At this time the pressure is approximately balanced by the lithostatic pressure and the shock wave breaks away from the cavity. While still in the neighborhood of the cavity the shock wave crushes the rock. Further out, fractures are produced whereas, at greater distances, the medium behaves elastically in response to the pressure wave. The resulting cavity stands for a period of time which depends upon the type of rock, the depth of burial and the explosion yield. When and if collapse occurs, it generally progresses upward at about the same diameter as the cavity until the limit of the fracture zone is reached. The resulting roughly cylindrical volume of broken rock and rubble is called the chimney. The time history of an underground explosion is shown in figure XXVI.

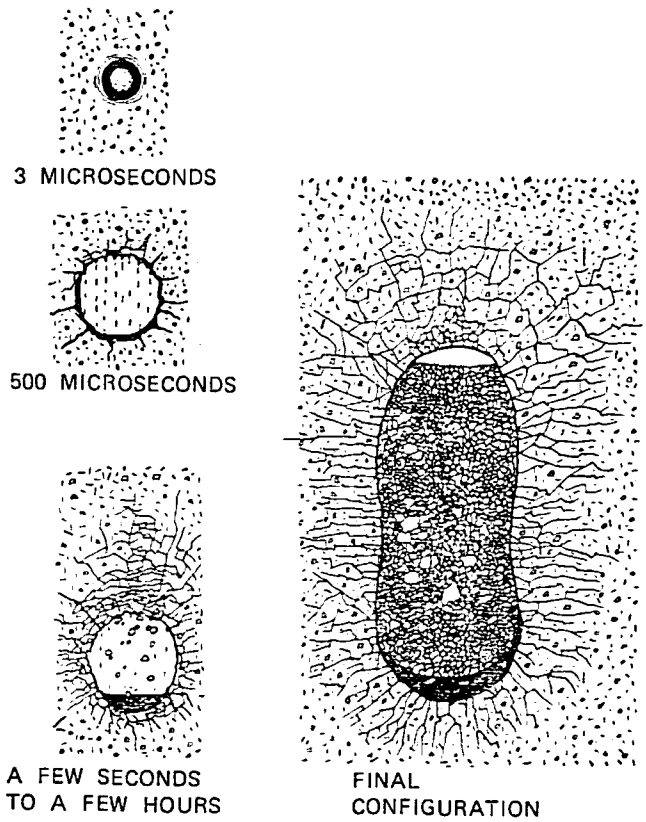


Figure XXVI. A typical sequence of events after a nuclear explosion is detonated underground (538)

278. If the explosion occurs at great depths,[7] all the radio-active products will remain underground. However, the crushing of rock and the formation of fissure systems may create channels from the cavity through the overlying layers to the surface and radio-activity may be released into the atmosphere. This process would usually require considerable time (of the order of an hour or more). This means that only the isotopes of inert gases or volatile elements (e.g., halogens) could escape into the atmosphere. The isotopes ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{133}Xe, ^{135}Xe, and ^{138}Xe would be the ones most efficiently released (278). If, however, the release were to begin a few minutes after

[7] The minimum depth for total containment depends on explosion yield and is approximately 140 m kt$^{-1/3}$.

the explosion, the short-lived ^{89}Kr, ^{90}Kr and ^{137}Xe might escape (278) and their decay products would settle on atmospheric dust particles, forming so-called secondary aerosols. It should be noted that this type of release is not likely to occur if the site of the explosions is determined after a careful study of its geology. It has not been observed after any United States contained explosion for peaceful purposes.

279. *Gas stimulation.* One of the most important possible applications of contained underground explosions is for recovering gas from known reservoirs from which gas may not be produced as efficiently by conventional methods. In these attempts to stimulate gas reservoirs, the chimney and fracture regions serve as a gathering system for the natural gas (251). In the Plowshare programme two gas stimulation experiments, Gasbuggy and Rulison, were performed. Data on these experiments are shown in table 48. These experiments demonstrated that the principal radio-nuclides remaining in the gas several months after the initial explosions were ^{3}H and ^{85}Kr (568, 569). From table 48 it is evident that the concentration of tritium in the Rulison gas is down by a factor of four compared with Gasbuggy, and that its total amount in the gas is also less by a factor of about two. However, neither of the devices used in those tests are specially designed for gas stimulation (209). The amount of residual ^{3}H per kiloton of yield will be considerably less in future United States gas stimulation experiments owing to the use of an explosive specially developed for that purpose (358). The only other activities observed in the Gasbuggy gas were due to ^{133}Xe, ^{37}Ar, ^{39}Ar and ^{14}C (252). The concentrations of the long-lived ^{39}Ar and ^{14}C in the early samples were about 0.1 and 1 pCi cm^{-3}, respectively.

3. *Cratering experiments*

(a) *Formation of crater*

280. When the explosion takes place at a relatively shallow depth,[8] there is a breakthrough of the cavity to the surface and ejection of radio-active products into the atmosphere (667). The size of the resulting crater, the shape of the explosion cloud and the particle properties of the airborne debris depend not only on the depth of burial and the explosion yield but also on the strength and water content of the ground material.

281. Explosions in dry hard rock result in a fast drop of the cavity pressure and the cratering will be caused mainly by the shock wave. The material overlying the expanding cavity will act as a filterbed through which the radio-active material must pass. As a result only a base-surge cloud (see figure XXVII) is formed which contains small particles mixed with finely-distributed ground material and enriched in volatile radio-active products. When the water content of the ground is high, the cavity pressure will drop more slowly and overpressure will contribute to the crater formation (330) causing a "dynamic venting" of gases and of primarily-formed particles. Besides a base-surge cloud this dynamic venting results in the formation of a main cloud (see figure XXVII) which reaches substantially higher into the atmosphere. Although at very early times the airborne activity is not grossly fractionated, the smallest particles are strongly enriched in volatile products.

[8] The minimum depth for cratering depends on explosion yield and is approximately 60 m $kt^{-1/3.4}$.

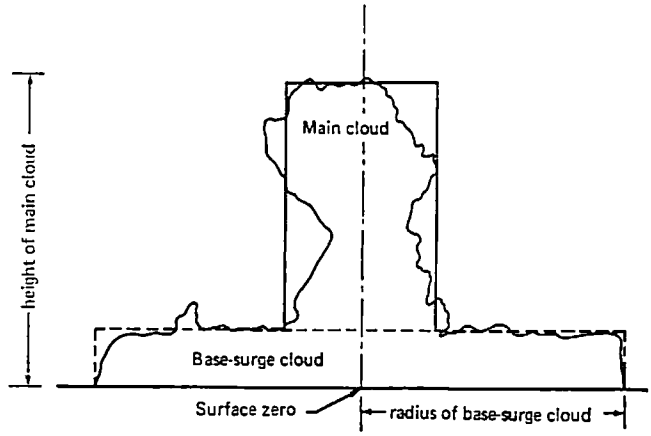


Figure XXVII. Definition of cloud dimensions (333)

282. At greater explosion depths, the ground between the cavity and the surface is lifted by the shock wave but falls back again so that no real crater is formed. A certain amount of dynamic venting may occur and release a small part of the still volatile products as well as some of the smallest particle fraction. Later on a slow seeping out of gaseous products (mainly noble gases and tritium) may occur through fissures in the ground material.

283. Probably the most widely known potential application of nuclear cratering is the construction of canals and specifically that of a sea-level canal across the American Isthmus. Of the four considered routes involving nuclear excavation techniques, a route through Colombia appears to be the least expensive by a considerable margin (210). It would require a total of 148 devices, amounting to a yield of approximately 120 megatons. The channel would be excavated in sections by about 20 separate rows of explosions, each consisting of from 5 to 16 nuclear devices which would be exploded simultaneously (271). According to an early estimate, about 115 million tons of dust would be airborne at one time or another as a result of the explosions (606).

284. In the Soviet Union, plans have been developed for the transport of additional water to the Caspian Sea which has been drying up in the past 15 years (668). The proposal is for the northward flowing Pechora River to be intercepted by a series of dams and canals, the water being diverted into the southward-flowing Karna River. One canal would be 112 kilometres long and would be built over 65 kilometres by nuclear means (250 charges). Up to 20 charges would be detonated simultaneously with a maximum explosive yield of three megatons.

(b) *Release and transport of debris*

(i) *Cloud geometry*

285. At the time of stabilization, the geometry of the cloud from a nuclear cratering explosion depends on explosion yield, explosion environment, depth of burial of the device and meteorological conditions during cloud formation (331). Figure XXVII shows the form of the main cloud and base surge cloud at the time of stabilization (333). Figures XXVIII and XXIX give the radius of the base-surge cloud and the main-cloud height, respectively. On increasing the water content of the medium surrounding the explosive, one can

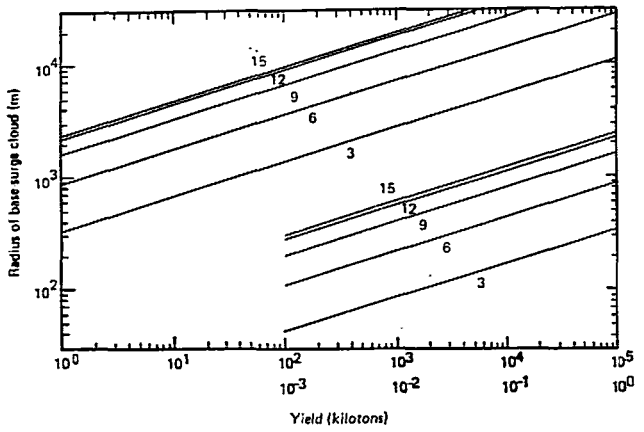


Figure XXVIII. Radius of base-surge cloud *versus* yield at scaled depth of burial of 3 to 15 m kt$^{-1/3}$ in alluvium (333)

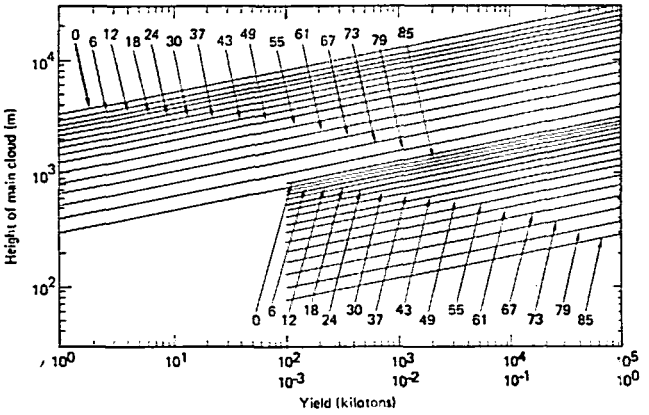


Figure XXIX. Height of main cloud *versus* yield at scaled depths of burial of 0 to 85 m kt$^{-1/3}$ in alluvium (333)

expect that the stabilized base-surge cloud would be larger (661) and that the main cloud and the vented fraction of refractory radio-nuclides would increase (333).

286. Lack of experimental data makes it difficult to predict the sizes of the resulting clouds from the explosions of nuclear row charges. However, the individual main clouds may be treated separately and their heights may be obtained from figure XXIX (333). At any rate, it is essential to follow up the evolution of the cloud. The radius of the resulting base-surge cloud would be about the same as that of a base-surge cloud formed in a single explosion with the same total yield and the same scaled depth.

(ii) *Deposition*

287. *Crater and lip.* A large part of the radio-activity produced in a nuclear cratering explosion is carried down by the fall-back which descends into the initial crater and its immediate vicinity. Figure XXX shows the exposure rate as a function of time for five different explosion yields (600). The exposure rate in the crater and lip area decreases as the explosion yield increases. This decrease is due to lower concentrations of radio-nuclides in the fall-back and ejecta. This in turn results from (*a*) a decrease with increasing yield (constant fission trigger) in the amount of radio-activity produced per unit yield; and (*b*) the increase in direct proportion to yield of the amount of material

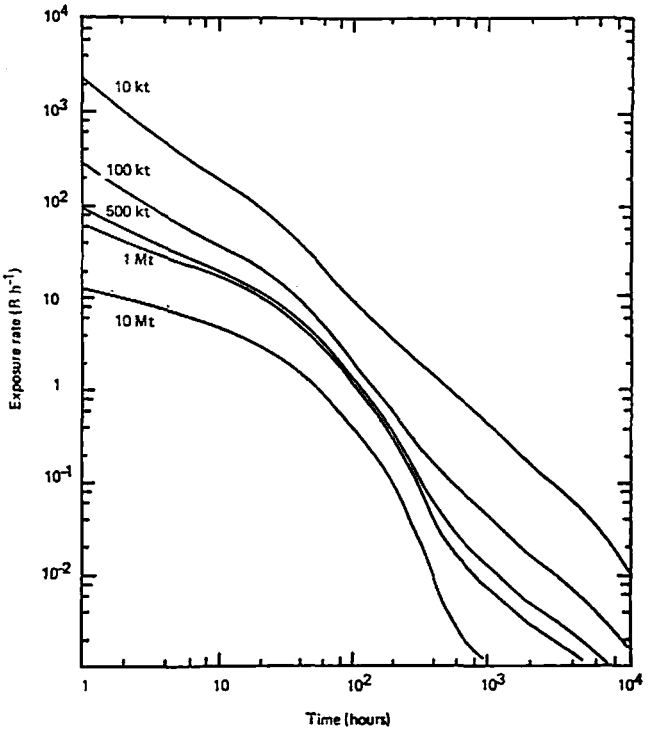


Figure XXX. Time variation of the exposure rate in the crater and lip area from 3 kt-fission explosions of different total yields detonated at a scaled depth of burst of 44 m kt$^{-1/3.4}$ (600)

which contains the radio-activity. The shapes of the curves change with yield because, as the yield increases, so does the relative contribution from the induced radio-nuclides (600).

288. *Local fall-out.* The large particles in the base surge and the main cloud descend within the first day and form the local or close-in fall-out. Figure XXXI shows, for explosions at different scaled depths, the percentage of the radio-active products deposited as

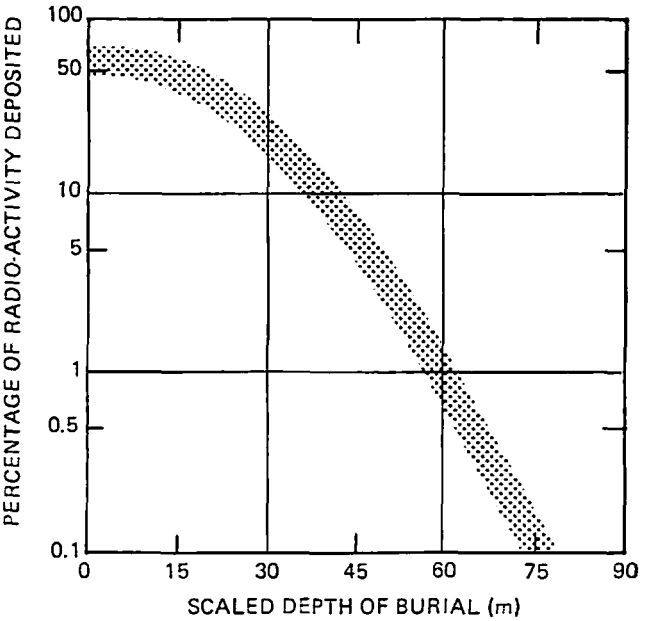


Figure XXXI. Percentage of radio-activity deposited as local fall-out in cratering tests (198)

local fall-out (198). The medium surrounding the explosive, and especially its water content, plays an important role which is reflected in the breadth of the band that describes the relationship in figure XXXI. Once the fraction of radio-active products present in the local fall-out is predicted, it is possible to calculate a fall-out pattern which can be used in planning safety measures. This is accomplished by using appropriate meteorological data (turbulence and wind speed as a function of altitude), distribution of debris of different particle sizes and initial cloud configuration (333).

289. *Long-range fall-out.* The very small particles may remain suspended in the air for considerable times before they reach the ground as long-range fall-out. The cloud dimensions continually increase as a result of turbulent diffusion. The cloud can thus be very large and the particles be brought to great distances by the wind before they descend to earth either by impact or by precipitation. With regard to the radio-activity present in the long range cloud, Crawford (333) has developed a diffusion model which enables the cloud concentrations to be estimated as a function of time and which also provides a means for determining the deposition of material from the cloud over considerable distances from the epicentre. Experimental findings indicate that the basic constituents of the long-range fall-out from cratering explosions are ^{89}Sr, ^{140}Ba and ^{91}Y which after about 10 days account for more than 80 per cent of the total activity (279). This distribution of fission products is due to the fact that among the precursors of these products in the mass chains are isotopes of krypton and xenon with half-lives ranging from 10 seconds to several minutes. Similar isotopic composition of long-range fall-out has been reported elsewhere (319, 336, 501). Devices of different designs may result in different distributions of radio-nuclides in long-range fall-out. Thus, ^{181}W and ^{185}W were reported to predominate in the long-range fall-out from the Schooner cratering explosion (table 49) (62, 99, 126, 141, 502).

(iii) *Ground-water contamination*

290. For contained underground explosions, the concentrations of radio-active products in ground water are dependent on several factors such as radio-nuclide production and initial distribution, radio-active decay, sorption on geologic material, and dispersion during hydrologic transport. For cratering explosions other aspects of the hydrologic cycle, particularly rainfall and the characteristics of the water table, must be considered (646). For contained explosions, where the cavity may collapse either completely to form a subsidence crater or partially to form a chimney, there are indications that the ground water close to the explosion point will flow inward toward the cavity for a considerable time, possibly years (583). After the restoration of the pre-explosion ground-water flow, the radio-nuclides will be transported away from their initial deposition by ground water along the regional hydraulic gradient. Tritium, which is readily available for transport and whose exchange with the rock matrix is negligible, is the only radio-nuclide in ground water likely to appear in significant concentrations at some distance from the explosion point. ^{90}Sr will be significantly retarded in its ground-water transport in practically all geologic environments; the rate of movement of ^{90}Sr will rarely be more than a few per cent of the average rate of ground-water flow (583). The small amount of ^{14}C produced may be considered insignificant when distributed in the large volume of material around an underground explosion. ^{137}Cs tends to be even more firmly held by sorption than is ^{90}Sr (583), while ^{60}Co is insignificant in comparison with the longer-lived ^{90}Sr.

4. *Doses*

291. Nuclear explosives for peaceful applications are still in the experimental stage. Cratering events have been conducted in isolated areas on a scale small by comparison to that of the projects to which they might be applied. A few practical applications of contained explosions have so far been made, all of them in the Soviet Union (table 49). Up till now, the doses received by the public have been extremely small. This section will review the doses received so far, and also indicate those that might be expected if some large-scale applications were carried out with the help of nuclear devices of current design.

(a) *Contained explosions*

292. An underground explosion successfully contained does not lead to any release to the environment, but if its purpose is to enhance the availability of oil or natural gas, the resulting products are likely to be contaminated to some extent. Four such experiments have been reported so far, two in the Soviet Union (321) and two in the United States (table 48).

293. In the Soviet Union, three charges were detonated several years ago in an oil deposit to increase the extraction of petroleum. The explosions produced no general radio-active contamination of the atmosphere or ground site, and the outputs of the wells which were increased over the entire field by 27-60 per cent over its normally-expected yield, showed no traces of non-gaseous radio-active contamination. The data regarding the second explosion, which was set off in a gas field, have not yet been reported (321).

294. The two United States experiments (Gasbuggy and Rulison) were conducted in natural gas formations. The only significant long-lived radio-nuclides found in the dry gas product were ^{3}H, ^{14}C and ^{85}Kr (568, 569). The contaminated gas was burned at the surface, instead of being marketed. The results of the off-site radiological surveillance for project Gasbuggy indicated that the project did not result in the introduction of any device-related radio-activity into the existing natural-gas distribution system (409). Future contamination of water supplies following hydrological transport of radio-nuclides is also very unlikely (573).

295. Although none of the gas from the Gasbuggy well had been introduced into the distribution system, theoretical evaluation of the potential radiation exposure from hypothetical domestic and commercial utilization of the contaminated gas have been reported (33, 285). The most important radiation exposures from ^{3}H and ^{14}C are likely to occur after combustion transforms CH_3T and $^{14}CH_4$ into HTO and $^{14}CO_2$, whereas ^{85}Kr is merely carried along with the natural gas. Table 50 presents the whole-body doses resulting from hypothetical distribution of all the Gasbuggy gas in the Los Angeles basin, where natural gas is used for fueling steam plants to generate electricity and for a wide variety of industrial and commercial applications, as well as for domestic consumption (33). Tritium would practically be the only contributor to the dose despite the fact that most of the amount produced

by the explosion was bound with water in the cavity where it did not seem to exchange appreciably to methane (252). The most critical pathway would be domestic consumption for space heating and cooking. For a given consumption rate of contaminated gas in a conventional dwelling, the dose from domestic use depends upon the fraction of combustion products vented inside the home, i.e. upon the relative amounts of gas used in nonvented and vented appliances and upon the efficiency of the venting system. The weighted average dose assumes that, in 10 per cent of the houses, the heating and other appliances making use of gas are unvented and that, in the other 90 per cent, only the kitchen range is unvented (33, 647). The dose resulting from ingestion of food and water that have been exposed to the combustion products has not been included, but experimental results indicate that it would only amount to 2 to 7 per cent of the total (285).

296. As the consumption of gas in the Los Angeles basin is much larger than the production of the Gasbuggy well, the contaminated gas was assumed to be diluted before distribution in that region. The hypothetical dose commitment resulting from the exclusive domestic use of *undiluted* Gasbuggy gas, in an area where the annual heating requirement is 2,800-degree Celsius-days (average value for the United States) (286) is 40 millirads. Assuming a production rate of 28 10^3 m^3 d^{-1} (285), more than 99 per cent of the dose would be received in the first year.

297. The population dose commitment would be about 200 man-rads if the contaminated gas were distributed in the Los Angeles basin and thus, to a certain extent, used for industrial purposes. The maximum population dose commitment would occur if all the gas were used for domestic consumption; in that case, it would be 700 man-rads if the gas were distributed in the Los Angeles basin (population 7 million) and 550 man-rads if the gas were distributed in an area where the annual heating requirement is 2,800-degree Celsius-days. After use, the tritium would be released to the atmosphere and would give rise to an additional dose commitment to the world population. This, however, would be quite small, as it corresponds to a population dose of the order of 10 man-rads.

298. From the radiation protection point of view, the analysis of the Gasbuggy experiment led to the conclusion that efforts should be directed to the reduction of production of ^3H by the explosion. From 1,400 Ci kt^{-1} in the Gasbuggy event, the ^3H production decreased to 250 Ci kt^{-1} in the Rulison event and is expected to be less than 20 Ci kt^{-1} in future gas-stimulation applications which would use a new explosive design (358). For the purpose of comparison, table 50 presents the whole-body doses which would be expected if the Gasbuggy experiment had been shot with the specially developed explosive and if the contaminated gas had been marketed in the Los Angeles basin. Those explosives have been envisioned to develop a field of 28 wells in Wyoming in the United States (647). Four 100-kiloton explosions would be used per well and the 28 wells would be drilled over a six-year period. The gas from this field would supply about 10 per cent of the demand in the Los Angeles basin, where the average whole-body dose commitments to the population of users would be 0.6 millirad from $^3H + {}^{85}Kr$, the dose from ^{85}Kr being about 10 times less than that from ^3H.

299. The lower limit of tritium production in a gas-stimulation explosion is estimated at 2 Ci kt^{-1} (209). If that limit were reached, the radiation exposures from ^3H and ^{85}Kr would be about equal.

(b) *Cratering explosions*

300. The nuclear clouds formed by the few cratering explosions which have been detonated did not reach the stratosphere (figure XXIX) and, as a consequence, the radio-activity produced, with the exception of long-lived gases, was deposited in a matter of weeks in inhomogeneous patterns particularly sensitive to scavenging by precipitation.

301. The doses to the public could best be derived from the knowledge of the deposition pattern of the radio-active debris following each cratering experiment. The United States and the Soviet Union have independently developed prediction methods to that purpose (332). Unfortunately, the published data on actual explosions do not indicate if the nuclear clouds crossed densely populated areas a few days after the explosion and are not sufficient to calculate the population doses.

(i) *Dose contribution from short-range fall-out*

302. In certain circumstances, milk contaminated with ^{131}I appears to be at least a rough indicator of the whole-body doses which might have resulted from cratering experiments. Table 51 presents levels observed around the Nevada test site where the six United States cratering events took place. Five tests gave rise to detectable levels in the local milk network surrounding the test site. This network samples mostly farms or dairies located in eleven western states of the United States. Only Sedan and Palanquin gave rise to detectable levels in the national network which analyses weekly composite samples pooled from farms dispersed over hundreds to thousands of square kilometres.

303. Study of milk contamination around the detonation site provides some information on the population doses resulting from the intermediate fall-out. Analysis of the potential radiation exposures to a child from nuclear excavation projects shows that, for deposition at one day after detonation, the thyroid dose from ^{131}I ingested via the forage-cow-milk pathway would be the most important (127, 175). However, since 1963, the cratering experiments were intentionally conducted during the colder half of the year with wind blowing towards the north to take advantage of the fact that dairy cattle were on dry food (384). As a crude approximation, the total external whole-body dose to man can be expected to be equal to the ^{131}I thyroid dose to infants.

304. Using the pessimistic assumptions that the milk contaminated at the maximum concentration level observed in the local network would be distributed to 5,000 people and that the concentrations reported by the national network would be representative of the milk levels in the whole state, the population dose to the thyroids of infants six months to two years old were roughly estimated from population and birth-rate data (541, 617). The population whole-body dose commitment, then calculated as the product of the total population thyroid dose to infants (1,200 man-rads) by the ratio of the total population to the infant population (about 40 in the United States) is estimated at 4.6 10^4 man-rads. Dividing by the world population (3.5 10^9) yields an average whole-body dose of 14

microrads. Owing to lack of data, the dose arising from the intermediate fall-out of the Soviet Union cratering tests has not been taken into account.

(ii) *Dose contribution from long-range fall-out*

305. In order to estimate the doses from long-range fall-out, the inventories of selected isotopes present in the main cloud and the base surge in the Schooner experiment (332) were assumed to be homogeneously diluted in the 40-50° N latitude band. The dose commitments were then estimated from the transfer coefficients and other data given in the section on atmospheric and surface explosions. Results are summarized in table 52. Besides ^{3}H, only ^{90}Sr and ^{137}Cs have been considered for internal irradiation because the transfer coefficients from deposit to diet are not sufficiently known for the other radio-nuclides listed in table 52.

306. Although it is realized that, as a result of continuous improvement in explosive design and differences in fission yield and conditions of explosion, the activities released by the tests varied widely, if it is tentatively assumed that the Schooner event is representative of the nine nuclear cratering experiments conducted so far, then the total dose commitments from long-range fall-out may be estimated by multiplying the results of table 52 by nine. The total population integrated external dose commitment is thus found to be of the order of 10^4 man-rads. Dividing by the world population yields a world average dose of three microrads.

307. Regarding the internal doses, the major contribution is furnished by ^{3}H. For a 170-kiloton explosion, the amount of ^{3}H expected to be released to the environment is estimated at two megacuries (table 47). Assuming that the amount of ^{3}H released is proportional to the total yield, the cratering experiments gave rise to a world-wide distribution of about three megacuries, which corresponds to an average dose commitment of six microrads, much greater than the contribution of ^{90}Sr and ^{137}Cs.

308. There is a significant potential for using nuclear explosives to accomplish large-scale construction projects at considerable savings in cost and time as compared to use of conventional construction techniques. The most documented project is the construction of a new Atlantic-Pacific interoceanic canal (paragraph 283). If the route through Colombia were to be adopted, an area of about 8,000 square kilometres would have to be evacuated mainly to guard against short- and intermediate-range fall-out. Recent estimates show that approximately 10,000 persons live within this area (271). If those people were not evacuated, they would receive estimated lifetime doses ranging up to 300 rads from external radiation alone.

309. Concerning the long-range fall-out, the trajectories of the clouds are expected to be such that most of the radio-activity would be deposited over the Pacific Ocean and that only a small fraction of the base surge would branch towards the Colombian mainland (127). However, ^{3}H and ^{85}Kr would eventually be distributed world-wide. The amount of ^{3}H released would be 1,400 megacuries—slightly less than the quantity produced by atmospheric testing (paragraph 166). The dose commitment to the world's population would be of the order of three millirads. The production of ^{85}Kr has been assumed from table 48 to be in the range 12-23 curies per kiloton of fission. If the fission yield of the explosive device, assumed constant regardless of the total yield, is taken as 90 tons (smallest fission yield reported in the nuclear experiments), then the total fission yield is 13 kilotons; the production of ^{85}Kr would then be in the range 150-300 curies and the corresponding whole-body dose commitment would be of the order of 10 picorads.

5. *Conclusion*

310. There is a wide spectrum of potential peaceful applications for nuclear explosives. In any nuclear cratering explosion, some radio-activity is inevitably released into the environment. Nuclear cratering techniques have been developed to the point where they can be used for relatively small projects, such as formation of water reservoirs, as demonstrated in the Soviet Union. Dose commitments from past events have been tentatively estimated and should be considered as merely indicative. They would probably have been lower if current explosive designs had been employed. For large scale projects, problems involving safety of the population living in the proximity of the explosion site seem to be strong limiting factors.

311. The future of contained explosions looks more promising as some applications would not result in a release of radio-activity to the biosphere. For example, elimination of a runaway gas well was safely conducted in the Soviet Union and the prospect of storing industrial radio-active wastes in cavities formed by contained explosives has attracted interest. In other applications, the release of radio-activity would be small and could be controlled to a large extent. The only significant contamination of the natural gas recovered after the gas stimulation experiments carried out in the United States was that due to ^{3}H and ^{85}Kr.

II. Power production by nuclear fission

A. Introduction

312. The increasing use of nuclear fission in power production calls for assessment of potential environmental contamination at present and in the future. Estimates of the growth of nuclear power vary but the highest given in table 53 indicate that the world generating capacity, which was about 20 GW(e) in 1970 (264), may increase to about 1,600 GW(e) by 1990 and to about 4,300 GW(e) by the year 2000 (581). This increase is partly due to the predicted rise in power demand and partly to the higher percentage (just over 60 per cent in 2000) of electrical power expected to be produced by nuclear fission.

313. An IAEA survey (264) lists 361 research reactors and 127 power reactors as being in operation in 1971. About half of the power reactors are either experimental with output below 20 MW(e) or have relatively low outputs of 20-100 MW(e). The remainder of the power reactors, which accounted for more than 90 per cent of the installed capacity in 1970, have outputs in the range 100-800 MW(e) and are in operation in a total of 12 countries.[9] There are many power reactors under construction with outputs up to 1,200 MW(e) and 319 are expected to be in operation by 1977.

[9] These are Canada, France, the Federal Republic of Germany, India, Italy, Japan, Spain, Sweden, Switzerland, the Soviet Union, the United Kingdom and the United States.

314. The nuclear power generated in 1970, calculated from the figures published by the IAEA (263), was 8.6 GW(e) y to which must be added the contribution (1.1 GW(e) y) from power stations for which the installed capacity is known and the load factor assumed to be 0.65. This load factor is an average value for power stations fully operational before 1970 (263). Other reactors which were not fully operational contributed 5 GW(e) to the total installed capacity of 20 GW(e). The total nuclear power generated during 1970 was thus estimated to be 9.7 GW(e) y corresponding to an over-all load factor of 0.5. This is assumed to apply also in the year 2000, although a substantial number of nuclear power reactors may then be operated only during periods of high energy demand.

315. The Committee noted that the largest part of the information on which it bases its conclusions comes from a very small number of countries among those in which nuclear power plants are used to generate electricity. The Committee does not discuss, in this annex, reactors used in other applications of nuclear power, for example, district heating, ship propulsion or experimental projects.

316. In common with other industries, the nuclear power industry gives rise to wastes which may occur in airborne, liquid and solid forms. Environmental contamination resulting from leakage or discharge of radio-nuclides in wastes will be discussed here step by step, from the mining of ore to the reprocessing of spent fuel. Dose commitments from current practice, and those expected to be incurred in the future as a result of the industry's expansion, will be estimated. The dose commitments considered here will be those which are related to normal conditions of operational variability and not to accidents leading to uncontrolled discharges to the environment.

B. Environmental pathways involving radiation exposure of members of the public

317. Radio-nuclides discharged in airborne, liquid and solid wastes may be transferred along environmental pathways which depend upon the physical and chemical nature of the nuclides. These radio-nuclides may then give rise to radiation doses which are either external, e.g. from radio-nuclides in air, on the ground or in sediments, or internal, e.g. from radio-nuclides deposited in tissues following intake into the body. Estimations of doses from discharges by the nuclear power industry are more likely to require consideration of local situations than those from weapons tests fall-out because members of the public are likely to be relatively near such installations. As a result of this, short-lived nuclides, e.g. certain isotopes of krypton and xenon, and radio-nuclides whose properties may make them of significance to man in a particular environment, e.g. water-borne ^{106}Ru, give radiation exposures to defined population groups following pathways that are not relevant to fall-out from weapons tests.

1. *Atmospheric pathways*

318. Radio-nuclides in airborne wastes may be discharged by the nuclear power industry in gaseous, vapour or particulate form. Dispersion of a plume of airborne materials in the atmosphere has been described by a gaussian distribution (593), and working methods for quantitatively predicting dispersion have been evolved (e.g. 85, 481, 482, 565). The basic methods apply to level ground in open country during meteorological conditions ranging from substantial solar heating of the ground, resulting in considerable turbulence, to inversion conditions when temperature rises with height above ground and turbulence is suppressed. Modifications of the basic methods may be necessary to take account of the presence of obstacles, e.g. buildings or trees, or of discharge from a stack.

319. Airborne radio-nuclides may be deposited by dry deposition resulting from very small-scale turbulent diffusion processes which lead to impaction and/or adsorption of radio-nuclides on surfaces (106). The dry-deposition velocity varies with the physical and chemical form of the radio-nuclide; an outstanding example of this variation occurs with iodine which may be discharged from the nuclear power industry in several different forms (22, 30, 107, 196). Radio-nuclides may also be deposited by means of wash-out by rain falling through contaminated air at a rate which depends on the rainfall rate and on the form of the airborne material (160, 161).

320. If iodine is deposited on pasture grazed by dairy cows, a proportion is transmitted to milk (paragraphs 214-215) which may subsequently be consumed by infants. This pathway is not important, however, for heavy elements such as uranium and plutonium, which are not absorbed significantly from the gut into the cow's bloodstream (116) and, hence, are not transmitted to milk. Nor is the pathway important in the many countries where milk is either not produced near nuclear power sites or does not contribute significantly to diet. Other pathways which may lead to internal radiation exposure of man involve deposition on growing crops and soil, and on pastures used for animals providing meat for human consumption. An additional pathway leading to internal irradiation is inhalation of radio-nuclides in the plume of airborne wastes from the stack; in the special case of tritiated water, intake also occurs by absorption through skin (472) (paragraphs 362 and 395).

321. Beta and/or gamma emitting radio-nuclides in the plume or deposited on the ground may give rise to external radiation exposure of man. Many of the fission-product noble gases emit both types of radiation, the beta component usually irradiating only the skin. The shorter-lived kryptons and xenons mainly irradiate populations which may be described as local (paragraph 359) in contrast to the longer-lived ^{85}Kr which irradiates local populations as the plume is dispersed downwind, and subsequently irradiates the world population when the ^{85}Kr is dispersed in the global atmosphere (652) (paragraphs 392 and 396).

2. *Pathways involving the aquatic environment*

322. Radio-nuclides may also be discharged by the nuclear power industry in liquid and solid wastes and enter the aquatic environment by mixing and leaching processes. Water-borne radio-nuclides may be further dispersed, or be re-concentrated on sediments or in biota (paragraph 323), as local and general movement of surface and ground water proceeds. This pathway leading to radiation exposure of man is more important for the nuclear power industry than for weapons tests, which have taken place mainly in the atmosphere. Mixing and exchange processes in the sea with special reference to radio-active waste disposal were reviewed in 1961 (261).

323. Re-concentration of radio-nuclides on inanimate matter or in biota depends critically on the specific nuclide involved, its chemical form, which may change with time due to reaction with other constituents of the water, and the presence or absence of a stable homologue acting as a carrier. It also depends on metabolic and/or physical characteristics of the biota and sediments. Whilst concentration factors ranging from just under one to about 10^5 have been observed in particular circumstances, these should not be applied in the course of dose estimations to situations where the conditions are unknown or different from those in which the factors were measured (109, 184). Measurements of ^{134}Cs and ^{137}Cs in environmental materials provide evidence of the complex situation involving the interdependence of contamination of biota and inanimate matter as a result of fall-out from weapons tests and discharges of these nuclides by the nuclear power industry (paragraphs 355-357).

324. Utilization of fresh and sea water provides many environmental pathways for internal radiation exposure of man. Exposure of local (i.e. not global) populations may result from consumption of contaminated fish caught recreationally (paragraphs 356, 357, 386, 390) or commercially (paragraphs 356 and 390), or of an edible seaweed marketed commercially (paragraphs 387-389). Tritiated water discharged in liquid wastes may result in radiation exposure to local populations who ingest contaminated water or locally-produced food-stuffs (paragraph 391), or to the world population when ^3H is dispersed in the water of the globe (paragraph 397). Radio-nuclides re-concentrated on estuarine silt may result in external radiation exposure of a few persons using the area for fishing (paragraph 390).

C. Assessment of radiation doses to members of the population

325. Doses incurred by the population can be assessed either by an adequate knowledge of the quantity discharged and of the transfer parameters involved (dispersion, re-concentration factors, etc.), or by means of a programme of environmental monitoring which is usually related specifically to pathways selected as being of greatest importance.

326. It should be recognized that both approaches have serious shortcomings for the dose assessments required in this report. Calculations based on transfer models are subject to considerable uncertainty due to the complexities involved in field conditions. In many cases, the simplified models available are unrealistic. Monitoring routines, on the other hand, are frequently geared to ensure compliance with accepted limits and therefore provide insufficient information on the very low doses which may be incurred by members of the public. An additional difficulty in the interpretation of monitoring results may be due to the presence of fall-out nuclides in considerably larger amount than that of the same nuclides discharged from the nuclear industry. Furthermore, in many instances the discharges are so small that the resulting environmental levels are too low to measure by usual techniques. In view of the small contribution by the nuclear power industry to total dose commitments to members of the public, there has been no requirement to date for more sensitive methods of analysis and dose estimation.

D. Exposures from mining and milling

327. The first stage in the nuclear power industry is mining of uranium-bearing ores. As explained in Part One of this annex, the isotope ^{238}U, which constitutes about 99.3 per cent of natural uranium, is the radio-active parent of a long chain of daughter products, of which ^{226}Ra, ^{222}Rn and ^{210}Po are the most important from the radiation protection point of view (paragraphs 74-75). The mining processes give rise to liquid wastes which may be of local interest.

328. Most of the uranium is leached from the ore during milling and recovered in the subsequent chemical treatment, but the majority of radio-active daughter products in raw ore remain in the mill waste (609). A study of ^{226}Ra balances at mills employing different processes showed that most of the ^{226}Ra is present as suspended solids in mill tailings, which consist of about 99 per cent of the ore fed to the mill and are discharged on to tailings piles (609).

329. Liquids from these piles drain into tailings ponds which allow deposition and retention of ore solids and associated radio-activity. This represents a basic minimum form of treatment. Evaporation from tailings ponds in dry climates or re-use of water may reduce substantially the quantity of radio-active daughter products which reach surface or ground waters (421). Chemical treatment of process streams may also reduce significantly the concentration of dissolved pollutants, including ^{226}Ra, ^{210}Pb and various chemical components (609).

330. Solids in tailings piles are estimated to have totalled about 83 million tonnes by 1969 in the United States alone (562). This accumulation is the result of the sudden demand for uranium during the increase in the nuclear weapons production experienced in the United States after World War II. At that time, technological efforts were concentrated on the development of ore-refining facilities and on economical refining processes, and little attention was paid to waste materials. As a consequence, effective waste treatment or containment was lacking for several years (562).

331. A comprehensive survey of about 30 uranium mills in the United States was undertaken by Merritt (421) in 1967; of these half were disused. The survey showed that operators of mills still in use were planning and conducting current operations with the objective of total containment of solids and of controlling the discharge of water-borne radio-active daughter products. A proportion of the uranium output of these mills is used by the nuclear power industry.

332. Information on environmental contamination by radio-active daughter products discharged from uranium mills relates only to the legacy of past practices for disposal of ore solids and contaminated liquids and is not relevant to future production of uranium for use by the nuclear power industry. The use of tailings as fill material in habitable structures in Grand Junction, United States, is discussed in annex D.

E. Exposures from fuel fabrication and enrichment

333. The process of fuel fabrication usually starts with the uranium-ore concentrates produced at the mills. These concentrates are further purified by chemical processing involving the use of nitric acid and

fluorine and, if fuel enriched with the ^{235}U isotope is required, the volatile uranium hexafluoride is produced. Subsequent to enrichment, usually in a multi-stage diffusion plant, this product is converted by various processes (involving ammonia as a gas or a dilute solution, steam and hydrogen) to uranium as dioxide or metal, as required (199, 534). The final stage in fuel fabrication involves the addition of cladding material.

334. Fuel fabrication and enrichment give rise to various types of wastes. Most uranium compounds are solid and conventional air-cleaning equipment is used to remove particulates from airborne wastes. The quantity of uranium and other chemicals in liquid wastes is reduced by suitable treatment before discharge to the environment; uranium wastes and contaminated plant and other equipment are buried under controlled conditions. No data on wastes discharged from fuel fabrication plants are available to the Committee; however, these wastes are of little significance from the radiation protection point of view as they consist at present largely of uranium.

335. Thermal reactors currently employed in power production use uranium fuel, but some advanced reactor types now under development are based on fuel consisting of mixed uranium and plutonium oxides or carbides. The addition of plutonium to the fuel does not radically alter the processes required in its fabrication, but it does have an influence upon the potential environmental effects of material discharged because of the high radio-toxicity of plutonium, particularly when inhaled. The plants required for producing plutonium fuel are designed to provide more thorough containment at all stages including storage of wastes.

F. Exposures from nuclear power reactors

1. *Origin and amount of radio-nuclides produced*

336. The production of power in nuclear reactors is accompanied by the formation of fission products and activation products. Studies of slow-neutron fission of ^{235}U and ^{239}Pu show that the masses of over 80 fission products generated during fission fall largely into two groups, a "light" group with mass numbers 80 to 110 and a "heavy" group with mass numbers from 125 to 155. Fission yields for the various mass numbers range up to over 6 per cent and vary with the fissile nuclide (199). Total ^{235}U and ^{239}Pu fission yields for nuclides of particular interest for this section are given in table 54, together with their radio-active half-lives.

337. Production rates of fission ^{3}H and ^{85}Kr are of interest because virtually all the activity produced is at present discharged to the environment during reprocessing. Data on production rates of ^{129}I are included with those for ^{3}H and ^{85}Kr in table 55 because some of the ^{129}I produced may be discharged to the environment and its radio-active half-life is very long ($1.7\ 10^{7}$ y). Production rates per MW(e) y are given for thermal and fast fission; in practice there will be a gradual transition from ^{235}U to ^{239}Pu, because many thermal reactors will burn a significant amount of ^{239}Pu produced from ^{238}U in fuel.

338. Annual production rates (table 55) of ^{3}H, ^{85}Kr and ^{129}I are calculated on the basis of (*a*) the power produced in 1970 (9.7 GW(e)) and (*b*) the estimated world capacity of 4,300 GW(e) in the year 2000 (table 53) consisting of 70 per cent fast-breeder reactors, as projected for the United States (465). Values are also given in table 55 for the integrated amounts produced and the cumulative amounts of these nuclides remaining when decay is taken into account. In all cases a load factor of 0.5 and a thermal efficiency of 0.3 are assumed. The values given for the year 2000 are very approximate as estimates of world nuclear generating capacity vary by a factor of about four (table 53) and the production rate of each of ^{3}H, ^{85}Kr and ^{129}I differs by a factor of about two according to the fissile material (table 55). The values for ^{3}H include only that produced by ternary fission in fuel.

339. Tritium is also produced by neutron activation of ^{2}H. In light-water reactors the rate is estimated to be about 0.004 Ci $(MW(e)\ y)^{-1}$, but in heavy-water reactors it could be as high as 30 Ci $(MW(e)\ y)^{-1}$ (505). Tritium in quantities intermediate between these values is also produced by activation of other reactor components such as boron and lithium used for neutron-density control (505) (table 56). These sources could add appreciable amounts to the ^{3}H produced by ternary fission, but the amounts vary too much depending on reactor design to be included in the estimates in table 55.

340. Besides ^{3}H, a large variety of activation products is formed in a nuclear reactor (table 56). Some of them, such as ^{134}Cs and some actinide radio-nuclides, are formed in the fuel and their activities can be calculated from data on burn-up and the neutron energy spectrum. The most important actinide radio-nuclide is ^{239}Pu which, being a fissile element, is also burnt up as fuel. Reported activities of ^{239}Pu in spent fuel are 160 Ci t^{-1} for fuel in advanced gas-cooled reactors (AGRs) (54) and 330 Ci t^{-1} for fuel in light-water reactors (LWRs) (465). ^{134}Cs is produced by neutron activation of ^{133}Cs, which is one of the most abundant stable nuclides formed by fission. ^{134}Cs activity in AGR fuel, after a burn-up of 18,000 MW(th) d t^{-1} at a specific power of 10 MW (th) t^{-1}, has been calculated to be about 20 per cent of that of ^{137}Cs (112).

341. The other radio-nuclides listed in table 56 are produced by activation of reactor components other than fuel. The cross-sections for production of those nuclides are given in table 56 but their activities cannot be calculated without a knowledge of the isotopic composition of the materials used in the reactor components and of the spatial distribution of the neutron flux and energy spectrum. Neutron irradiation of graphite or of carbon dioxide leads to the production of ^{14}C and irradiation of ^{16}O contained in air or water results in the formation of ^{13}N and ^{16}N. ^{41}Ar is produced by activation of air which contains ^{40}Ar in the proportion of about 1 per cent. The presence of chromium, cobalt, or zinc in metals gives rise to the formation of ^{58}Co, ^{60}Co, ^{51}Cr and ^{65}Zn.

2. *Discharges to the environment*

342. The emphasis in this report is on data which specify individual radio-nuclides discharged and which are, therefore, relevant to the estimation of radiation doses to man. Data on discharges are not available for some of the operating reactors and are limited in scope for others, being mainly in the form of gross activity measurements. Comprehensive studies giving information on individual nuclides discharged have been carried out in the United States on a boiling-water reactor (BWR) (304) and a pressurized-water reactor (PWR) (303). These are both light-water reactors

(LWRs). In addition, a detailed study has been made of the Hudson River (USA) to which radio-nuclides from a PWR are discharged (357). There is a small amount of information for similar reactors in other countries.

343. Limited information on individual nuclides discharged is available for gas-cooled reactors (GCRs) (88, 146, 499) and pressurized heavy-water reactors (PHWRs) (400). Discharges of noble gases from all of the above types of reactors are relatively well documented. Other reactor types, such as fast breeder reactors (FBRs) and organic moderated and cooled reactors (OMRs), are still at the development or design stage, and no information on discharges is available.

(a) *Liquid discharges*

344. Tritium is present in the coolant of water-cooled reactors (paragraph 339) and some of this is discharged with miscellaneous liquid wastes arising in connexion with reactor operation. Quantities discharged in each of the years 1968-1970 are given in table 57, which also shows the quantities of ^{3}H discharged per unit of power generated. It is clear that PWRs and the PHWR have discharged much more ^{3}H than BWRs. Various causes contribute to the difference. The use of dissolved boron in PWRs and of heavy water in the PHWR gives rise to considerable quantities of activation product ^{3}H in the coolant. Stainless-steel cladding used on fuel elements in the first four PWRs listed in table 57 allows greater diffusion of fission product ^{3}H into the coolant than the zircaloy cladding on fuel elements used in Dresden-I (BWR) and Ginna (PWR) in the United States.

345. Discharges of ^{3}H in liquid wastes from gas-cooled reactors in 1969 and 1970 are given in table 58. These vary considerably from station to station, but are on average somewhat more than those from BWRs and less than from PWRs in total quantities discharged and quantities per MW(e) y of power generated. The ^{3}H is partly fission-product ^{3}H from cooling ponds and the gas-coolant drying plant, and partly activation-product ^{3}H (146).

346. Individually-measured radio-nuclides discharged in liquid wastes are listed in tables 59 and 60 for water- and gas-cooled reactors, respectively. They are discharged as mixtures of fission and activation products. The nuclides are often very difficult or costly to measure individually, and the usual practice is to estimate gross beta and gamma activity only, unless this is abnormally high.

(b) *Discharges of noble gases*

347. Discharges of noble gases constitute the main source of external radiation around reactors. A very small proportion of the ^{85}Kr in fuel is discharged at reactor sites and all the remainder is released from fuel during reprocessing. Discharges of ^{85}Kr to the environment are discussed in paragraphs 377-378. In general, the total noble-gas activity discharged, which consists mainly of kryptons and xenons, is highest in BWRs and lowest in PWRs (table 61).

348. Activation gases are discharged from some reactors, particularly some GCRs and PHWRs (table 61). Activation of subsidiary-cooling air leads to discharge of ^{41}Ar at a rate which depends on the characteristics of the reactor; discharge of gases activated in the primary coolant occurs as a result of leakage and of operational need (262).

349. In LWRs, discharges consist mainly of fission gases which enter the coolant from fuel. The composition of noble fission gases is presented in table 62 for various decay times. In BWRs, gases are discharged after a 20-30 minute hold-up of the off-gas stream to achieve removal by decay of most of the original activity (324). Table 63 shows that the measured composition of gases discharged from the Dresden-I BWR agrees reasonably well with results computed for a 21 minute decay.

350. In PWRs, gases are discharged when the coolant is depressurized after a hold-up time of up to 120 days. Values for the discharge of radio-active gases from PWRs, which consist mainly of ^{133}Xe, are shown in table 61.

(c) *Other gaseous and particulate discharges*

351. Discharges of other gaseous and particulate radio-nuclides to atmosphere are usually reported in general terms, such as halogens and particulates. Information available for ^{3}H and gaseous ^{131}I is summarized in table 64. The tritiated water discharges from the PHWR at Douglas Point in Canada resulted largely from the high production rate of ^{3}H in the heavy-water coolant and moderator (400). The discharges of ^{131}I from Dresden-I, Yankee Rowe and Douglas Point reactors were less than one curie per year, although the total ^{131}I content of these reactors when at their full power of about 200 MW(e) is of the order of 10^{7} curies. Discharges of particulates from Dresden-I and Yankee Rowe were also well under one curie per year (303, 304), while airborne particulates from the PHWR are removed by filtration and are not normally present in detectable quantities (400). As well as ^{41}Ar, ^{14}C and the short-lived ^{16}N, the radio-nuclide ^{35}S has been reported as a constituent of GCR stack gases in the United Kingdom (499).

3. *Doses resulting from environmental contamination*

(a) *Doses from radio-nuclides discharged to the aquatic environment*

352. Radio-nuclides are discharged to rivers, sometimes in tidal reaches, or to large lakes from all the water-cooled reactors listed in table 57 except Oyster Creek and San Onofre, from which they are discharged directly to the Atlantic and Pacific Oceans, respectively. Radio-nuclides are discharged to the coastal waters of the British Isles from all the United Kingdom gas-cooled reactors listed in table 58, except those at Trawsfynydd from which they are discharged to a fresh-water lake. In the case of the reactor at Latina in Italy, they are discharged to the Mediterranean.

353. The highest measured values of tritium concentrations in environmental samples near three PWR sites quoted by Krieger *et al.* (345) relate to discharges and not to water available for intake by members of the public. The only published estimates of the very low doses to local populations due to tritium discharged are based on conservative assumptions of dilution and intake (59, 345, 400).

354. Detailed environmental studies have been conducted near two of the water-cooled reactors in the

United States for which data on specific radio-nuclides in liquid discharges are given in table 59. The study in the Illinois River near the Dresden-I reactor took place during a nine-month period in 1968 (304) and a comprehensive research programme on the Hudson River estuary, into which radio-nuclides from the Indian Point-I reactor are discharged, was carried out from 1964 to 1970 (357). A comprehensive monitoring programme is also in operation on the coastal waters of the British Isles into which four of the reactor sites listed in table 60 discharge their wastes, and on Lake Trawsfynydd to which the fifth site discharges (426, 427).

355. Monitoring results require considerable interpretation before an estimate of doses to members of the public can be made. For example, as ^{137}Cs is often the nuclide which contributes most of the dose when contaminated fish or other aquatic food-stuffs are eaten by humans, it is desirable to distinguish ^{137}Cs from reactor operations from that in fall-out. The presence of the shorter-lived isotope ^{134}Cs in the former is of assistance here and its use is suggested in the studies of the $^{134}Cs/^{137}Cs$ ratio in biota in the brackish water of the Hudson River. These studies indicated that intake of caesium by the biota was mainly from freshly introduced caesium isotopes from the reactor rather than ^{137}Cs from fall-out retained on bottom sediments (357).

356. Mean caesium concentrations measured in fish at Dresden-I, Indian Point-I and Trawsfynydd are shown in table 65. The mean ^{137}Cs concentration of 0.015 pCi g^{-1} wet in various species in the Illinois River near Dresden-I is the average of upstream and downstream values because there was no significant difference between them. The discharges of radio-caesium into the Hudson River from Indian Point-I produced a measurable difference between upstream and downstream samples for both ^{134}Cs and ^{137}Cs and, in this case, it is possible to calculate doses resulting from material discharged. The dose from both isotopes was estimated to be 10^{-6} rad y^{-1} per g d^{-1} of fish consumed (table 65). Commercial and recreational fishing take place in the affected reaches of the Hudson but neither the fish consumption rates nor the size of the population involved are known. Other nuclides (^{58}Co, ^{60}Co and ^{54}Mn) were also measured in fish, but they did not add appreciably to the dose due to the radio-caesium discharged.

357. Mean caesium concentrations measured in trout and perch from the lake at Trawsfynydd (426), where about 100 persons consume fish caught recreationally (323), are shown in table 65. Although some of the ^{137}Cs in fish from Lake Trawsfynydd may be from fall-out, the ratio of $^{137}Cs/^{134}Cs$ in the fish in 1969 was similar to that in the discharge in that year. The total annual whole-body dose due to radio-caesium is estimated to be 2 10^{-4} rad y^{-1} per g d^{-1} of fish consumed (table 65). Values for 1970 were somewhat lower than those for 1969 (427).

358. Population dose commitments from discharges from three United Kingdom reactor sites are shown in table 66 (323). The dose commitments have been taken to be equal to the annual doses (thus implying that the various components of the food chain are in equilibrium). In the table, individual and population dose commitments are based on the consumption and exposure rates quoted for the exposed population groups.

(b) *Doses from noble gases discharged to atmosphere*

359. Noble gases in airborne wastes cause external radiation exposure which decreases rapidly with distance from the reactor as a result of the short half-life of most of the gases discharged and of dispersion of the plume in the atmosphere. Annual doses to populations living in the vicinity of nuclear power plants are a function of the population distribution, meteorological characteristics and distance from the site boundary. Average annual doses in 1969 (table 67), both at the site boundary and for the population included within 6.4 and 80 kilometres of these plants, have been calculated (188) using realistic population distributions and wind frequencies for 11 power reactor sites in the United States and average meteorological conditions. Because no allowance has been made for the time spent in buildings and the shielding afforded by them, these doses are overestimated. As expected, the doses vary widely from one power plant to another and in the case of BWRs are much less for new reactors than for old ones because of technical improvements. The population dose beyond 80 kilometres will depend upon the amount of comparatively long-lived nuclides, particularly ^{133}Xe, present in the discharge. The ratio between the long-distance and the short-distance contributions to the population dose will increase if the radio-active gases are stored for a period sufficient to allow the short-lived components to decay, thus increasing the proportion of longer-lived components in the mixture. The contribution from ^{85}Kr is insignificant because most of the ^{85}Kr is released from the reprocessing plants (paragraph 369).

360. Estimates of doses at the site boundary of some of the reactors listed in table 61 are shown in table 68. Where annual doses at or near the boundary have not been reported, they have been estimated using the assumptions indicated in the table.

(c) *Doses from radio-nuclides following other pathways*

361. A survey in the vicinity of the Dresden-I reactor, where discharges in 1968 of a number of radio-nuclides to atmosphere and the aquatic environment were up to one curie (tables 59 and 64), showed that few of the environmental samples contained any activity attributable to the discharges (304). ^{131}I was measured in thyroids of heifers allowed to graze on pasture for several weeks before slaughter, specifically as indicators of contamination, but was not detected in milk from a herd at the nearest dairy. This and other negative results in a range of other environmental materials, including cabbage, deer and rabbit, led to the conclusion that exposure to the surrounding population through consumption of food and water from radio-nuclides discharged from Dresden-I was not measurable.

362. Doses may be incurred by the population at large living near reactors from which tritiated water is discharged to atmosphere. If ^{3}H intake is limited to inhalation and passage through the skin, drinking water and food being uncontaminated, the dose at the boundary fence is calculated to be 7 10^{-7} rad $(MW(e)\ y)^{-1}$ for the Douglas Point PHWR (400). Considerably smaller amounts of ^{3}H are discharged from reactors of other types (table 64) and the doses are correspondingly lower. The contribution of ^{3}H discharges to global doses is discussed in paragraph 397.

G. Exposures from fuel reprocessing and waste disposal

1. *Fate of the radio-nuclides in fuel fed to a reprocessing plant*

363. At the end of its useful life in the reactor, fuel is removed and immersed in a cooling pond at the reactor site to allow substantial decay of many short-lived nuclides. This decreases potential radiation and other hazards during subsequent handling, transport and reprocessing of fuel, and simplifies the recovery of valuable fissile materials, e.g. ^{239}Pu and uranium.

364. The principle widely employed in reprocessing plants is to separate plutonium and uranium from fission products by a multiple-stage extraction process that leaves the fission and corrosion products in aqueous solution. The aqueous solution from the first extraction usually contains more than 99.9 per cent of the fission products from the dissolved fuel (611); this highly radio-active solution is often concentrated by evaporation before storage in specially constructed and protected steel tanks, sometimes located underground. In some cases the solution is allowed to boil, in others it is cooled, but there is always a gaseous stream which may carry entrained fission products from the solution. This process stream is filtered before being discharged to the environment.

365. Although the storage of highly radio-active solutions has been satisfactory hitherto, potential problems associated with long-term maintenance and supervision of containment have led to investigation of methods of permanent disposal (547). The principle common to most of the methods is to convert the solution to suitable solid material that will withstand effects of high radiation levels, and to store or bury it in selected man-made or natural locations. There would be little airborne or water-borne radio-activity released from stored solidified wastes, but clean-up problems of gaseous process streams might be severe during solidification processes. The decision to apply the principle of solidification has already been made in the United States, where liquid storage is to be permitted only during the first five years after reprocessing (43).

366. Various aqueous solutions of fission products of relatively low activity concentration are produced as a result of the washing of organic solutions of plutonium and uranium separated from the bulk of the fission products during the multiple stage process. In some cases, chemical or other treatment may be employed to reduce the quantity of many of the radio-nuclides in these solutions, before they are mixed with other lower-activity solutions. The latter may arise from the decontamination of process equipment, protective clothing and personnel, as well as from scrubbers or similar devices used to remove radio-activity from gaseous streams. At present these waste solutions, which may be of very large volume, are discharged to the environment by way of dry wells or open pits in the ground (618) or directly into the sea (253).

637. The aqueous waste currently discharged to the environment contains, as tritiated water, virtually all of the fission-product ^{3}H present in fuel at dissolution (table 55), although advanced technology may reduce the rate of discharge from future reprocessing plants by factors of 10 to 100 (465). For the same reason that ^{3}H is practically unrecoverable after tritiated water has been diluted with ordinary water, ^{3}H will not be expected to concentrate in biological material.

368. Other radio-nuclides present in fuel whose characteristics make them of interest in the present context are the noble gases ^{85}Kr and ^{133}Xe, and two isotopes of iodine, ^{129}I and ^{131}I.

369. Almost all of the ^{85}Kr produced in thermal reactors (table 55) remains in the fuel until dissolution, unless the cladding becomes defective in the reactor. The normal cooling time of about six months does not materially affect the amount of ^{85}Kr available for discharge because its half-life is relatively long (10.7 y) but methods have been developed to absorb and store the gas for a period of several half-lives (149, 420, 566).

370. The fission product ^{133}Xe has a short half-life (5.3 d) and its equilibrium level is about 1 MCi t^{-1} at a power level of 20 MW(th) t^{-1} (table 54). The activity decays to 10^{-4} Ci t^{-1} when fuel is cooled for about six months. If fast-reactor fuel is cooled for only 30 days before reprocessing, the corresponding content would be about 2 10^{4} Ci t^{-1}. The ^{131m}Xe content of fuel is two orders of magnitude less than ^{133}Xe (table 54) but its longer half-life (12 d) results in a slower rate of decay than with ^{133}Xe. Several processes involving hold-up on a charcoal bed may be employed to produce an order of magnitude reduction in the radio-xenon activity discharged (465).

371. Because of its very long half-life (1.7 10^{7} y), virtually all of the ^{129}I produced in small amounts in nuclear fuel (about 0.02 Ci t^{-1}) is present at the time of dissolution (87, 537). ^{131}I has a half-life of only eight days and after the usual cooling period for thermal-reactor fuel of about six months, the ^{131}I content of fuel is about 0.1 Ci t^{-1}. It is normal practice to employ general-purpose scrubbers with a decontamination factor of up to 1.000 to reduce the amounts of airborne radio-iodine discharged from the plant (90, 465).

372. The reprocessing of short-cooled fast-reactor fuels is likely to be part of a combined fast- and thermal-reactor programme because there will be a strong economic incentive to reduce to a minimum the quantity of plutonium required for the whole power programme. Investigations into control of airborne ^{131}I discharges during reprocessing of such fuel have shown that process streams will require decontamination factors well beyond those currently in use (90, 465). Because of this, discharges of ^{129}I will also be much less than the quantities in the fuel reprocessed.

2. *Discharges to the environment*

(a) *Liquid discharges*

373. The quantity of radio-nuclides discharged to the environment from reprocessing plants depends largely upon waste-management practices. These, in turn, depend upon the characteristics of the local environment and population and on the requirement of ensuring compliance with accepted radiation protection criteria. At the first commercial reprocessing plant (Nuclear Fuel Services, NFS) in the United States (393) low-activity solutions are discharged to lagoons which provide additional decontamination through settling during storage. Liquids from the lagoons are then discharged to creeks and rivers in the environment.

374. Data for individual nuclides discharged from NFS during a six-month period of special study in 1969 are given in table 69. Investigation of the distribution of the various radio-nuclides between dissolved and suspended solids showed that most of the ^{60}Co, ^{90}Sr, ^{106}Ru and ^{125}Sb were discharged in a soluble form and almost all of the ^{54}Mn, ^{95}Zr, ^{144}Ce and ^{147}Pm were discharged in an insoluble form, whereas ^{134}Cs and ^{137}Cs were discharged in both soluble (70 per cent) and insoluble forms (393). The only nuclide discharged from NFS for which data are available over a longer period is ^{3}H (373). These are given in table 70 and show that quantities varying from 3 to about 100 curies of ^{3}H were discharged per tonne of fuel processed.

375. Discharges of low-activity solutions from the reprocessing plant at Windscale in the United Kingdom are made to the Irish Sea through a pipeline terminating about 2.5 kilometres offshore. Measurements for three of the nuclides discharged are shown in table 69; these are required by the terms of the authorization for discharge (323). The composition of the effluent has changed over the operational period of 18 years, and is still changing slowly (323).

376. The low-activity solutions from the Eurochemic reprocessing plant at Mol, Belgium, are sent to the waste-treatment plant of the Belgian Nuclear Centre. Discharges from this plant are made to a tributary of the main Neet River and data for ^{90}Sr, the only individual nuclide quoted, are given in table 69 (625).

(b) *Discharges of noble gases*

377. The special study carried out at the NFS reprocessing plant showed that, although essentially all the available ^{85}Kr was discharged during dissolution of the fuel, up to 1 per cent was discharged during the chopping operation prior to dissolution (113).

378. No noble gas discharge measurements are available for the Windscale reprocessing plant in the United Kingdom or the Eurochemic plant at Mol in Belgium. However, ^{85}Kr discharges from the Eurochemic plant have been estimated (13), and estimates of discharges resulting from a predicted British nuclear power programme have been published (149). The Committee has estimated ^{85}Kr discharges from future power production (table 55) on the basis of 510 Ci (MW(e) y)$^{-1}$ for thermal reactors and 270 Ci (MW(e) y)$^{-1}$ for fast reactors (assuming a thermal efficiency of 0.3). The activity discharged to the environment may be less than that present at dissolution if steps are taken to absorb and store the gases (paragraphs 369 and 370).

(c) *Other gaseous and particulate discharges*

379. Tritium discharged through the stack to atmosphere was measured during dissolution of the two batches of fuel in the NFS and the amount (table 71) was estimated to be about 1.5 per cent of the total available (113). Preliminary data indicated that elemental ^{3}H was less than 10 per cent of the total ^{3}H discharged to atmosphere.

380. Discharges of ^{129}I from the NFS plant (table 71) were approximately 5-10 per cent of the total available; the fuel had been cooled for unusually long periods and the scrubbers were not in operation during these dissolution cycles. The use of scrubbers is estimated to reduce discharges to about 0.5 per cent of the available radio-iodine activities (113). Data on the average particulate activity discharged during dissolution of five one-tonne batches of fuel at the NFS plant are given in table 71 (calculated from data in reference 113). These results show that no particulate discharges to atmosphere exceeded about 10^{-7} Ci (MW(e) y)$^{-1}$.

381. A study of ^{131}I balances at the Windscale plant, which normally reprocesses fuel cooled for about six months, indicates that on average about 5 10^{-4} Ci d^{-1} is discharged to the atmosphere compared with 0.4 Ci d^{-1} to the sea in liquid wastes out of about 0.5 Ci d^{-1} fed to the plant (90). Similarly, about 0.1 per cent of ^{129}I in fuel would be expected to be in current discharges to the atmosphere.

382. The expected discharges of particulate ^{90}Sr, ^{137}Cs and ^{144}Ce from the Eurochemic plant, calculated on the basis of design figures (13), are two orders of magnitude greater than measured discharges from the NFS plant, normalized to the same rate of ^{85}Kr discharge. Predicted discharges of ^{239}Pu from Eurochemic are three orders of magnitude greater than measured discharges from NFS when normalized.

383. The development of nuclear power programmes and the increased use of fast-breeder reactors will result in a large increase in the ^{239}Pu treated in reprocessing plants. In the United States, the annual production is predicted to be 20 tonnes during the decade 1970-1980, and 80 tonnes by the year 2000, when plutonium-fuelled reactors may account for 50 per cent of the country's total energy consumption. Whether plutonium attains its predicted role in the future power economy may depend entirely on attainment of economic methods of preventing its discharge to the environment (354).

3. *Doses resulting from environmental contamination*

384. Data on environmental contamination and consequent doses to members of the population are presented for two reprocessing plants, the Nuclear Fuel Services plant near Buffalo in the United States and the Windscale plant of British Nuclear Fuels Limited in the United Kingdom. These were selected because they are plants known to include in their throughput a high proportion of fuel derived from reactors producing electricity commercially. The Eurochemic plant at Mol in Belgium should also be included but information about the amounts of radio-nuclides discharged is limited to ^{90}Sr and no information is available to the Committee on the levels of contamination in food-stuffs consumed by the population.

(a) *Doses to local populations due to discharges of radio-nuclides to the aquatic environment*

385. Data on environmental contamination in 1968 in the vicinity of the NFS reprocessing plant, which discharges liquid wastes to a creek, were used to make dose calculations for that year (556). The special study on liquid discharges was made during 1969 (data in table 69), so it is not possible to correlate monitoring results and discharge data.

386. The mean concentrations of ^{137}Cs and ^{106}Ru in fish caught in the creek are given in table 72; the mean concentration of ^{90}Sr is not included in the

table because the values were measured for whole fish and most of the ^{90}Sr will be in inedible bone (556). The mean ^{137}Cs concentration of 0.63 pCi g^{-1} in fish corresponds to an annual dose of 2 10^{-4} rad for a typical fish consumption rate of 15 g d^{-1} by members of the population. Similarly the mean concentration of ^{106}Ru of 0.85 pCi g^{-1} corresponds to an annual dose to the gastro-intestinal tract equal to 9 10^{-4} rad. Assuming that the 1968 operations are typical, the annual throughput of fuel irradiated to about 20 MW(e) y t^{-1} is 140 t y^{-1} (table 70) and these annual doses therefore correspond to about 10^{-7} and 3 10^{-7} rad (MW(e) y)$^{-1}$ for ^{137}Cs and ^{106}Ru, respectively (table 72). However, the numbers of people to which these doses are applicable is not stated but the numbers are probably small since the consumption of fish in the sampling area is the result of recreational fishing only.

387. A comprehensive marine monitoring programme is employed in connexion with the liquid discharges from Windscale (426, 427, 654). The critical pathway involves a type of edible sea-weed which is used in making laverbread in South Wales, 500 kilometres away. The sea-weed is monitored *inter alia* for $^{95}Zr/^{95}Nb$, ^{106}Ru and ^{144}Ce, and a study in 1967-1968 showed that ^{106}Ru contributed 82 per cent of the dose to the gastro-intestinal tract (425).

388. The ^{106}Ru concentrations in laverbread of 15 and 7 pCi g^{-1} wet in 1969 and 1970, respectively (table 72), are average values for the products of three manufacturers (426, 427). Intensive market surveys in South Wales have shown that the median rate of consumption of laverbread by a small critical group (about 100 persons) is 160 g d^{-1}, and that consumption by the whole group of 26,000 laverbread eaters is about 10 per cent of this (512). Average annual doses to the gastro-intestinal tract of the whole group of laverbread eaters, as result from ^{106}Ru contamination, were 1.7 10^{-2} and 8.0 10^{-3} rad per 16 g d^{-1} consumed in 1969 and 1970, respectively (table 72).

389. If the average annual throughput of the Windscale plant is taken to be about 1,800 tonnes of fuel irradiated to a level of 3 MW(e) y t^{-1}, the annual plant throughput corresponds to the generation of about 5,000 MW(e) y. Thus the above annual doses are equivalent to 3.4 10^{-6} and 1.6 10^{-6} rad (MW(e) y)$^{-1}$ to members of the whole population of laverbread eaters in 1969 and 1970, respectively. The contribution from this pathway to the population dose commitment to the gastro-intestinal tract is therefore about 0.09 and 0.04 man-rad (MW(e) y)$^{-1}$ in these years. The contribution to the population gonad dose is lower by a factor about 1,000 (88).

390. Dose commitments to small groups exposed through other pathways are given in table 73. The contribution to the population dose is, however, very small because of the small numbers of individuals exposed as well as the generally smaller individual dose commitments. On the other hand, plaice is fished commercially over a wide area of the Irish Sea and radio-caesium contamination of the fish is estimated to give rise to a population whole-body dose commitment of 3 10^{-2} man-rad (MW(e) y)$^{-1}$ (427). This is over three orders of magnitude greater than the population whole-body dose commitment resulting from consumption of fish by the much smaller group of 100 persons (table 73).

391. Concentrations of ^{3}H have been measured in various local food-stuffs around the NFS plant (556). Although ^{3}H discharged to the atmosphere may have contributed to amounts of this nuclide in such food-stuffs as deer meat and milk, the fraction coming from this source (1.5 per cent of the total discharged) is probably small compared to that coming from liquid discharges. Observed levels in milk were similar to those to be expected from ^{3}H released by the testing of nuclear weapons in the atmosphere. Levels in fish were about 10 times greater than those expected from fall-out alone while levels in deer were about 30 times greater. The latter results suggest that the deer were obtaining drinking water from the creek at points closer to the plant than the points where the fish were sampled. Members of the public eat deer meat and fish caught in the area, but Shleien (556) concluded that doses from ^{3}H to individuals eating typical amounts of these local food-stuffs were negligible.

(b) *Doses to local populations from discharges of noble gases to atmosphere*

392. Assuming a ^{85}Kr discharge of 510 Ci (MW (e) y)$^{-1}$ (table 55), the average rate of discharge of this nuclide from a plant processing fuel from a thermal reactor at the rate of 1 MW(e) y annually is about 1.6 10^{-5} Ci s^{-1}. At a distance of a few kilometres the long-term mean concentration in ground-level air is about 10^{-7} Ci m^{-3} per Ci s^{-1} discharged (85) so that the concentration near the plant would be about 1.6 pCi m^{-3} and the gonad dose commitment 2.7 10^{-8} rad (MW(e) y)$^{-1}$. The actual dose received by members of a population near a reprocessing plant would, of course, depend on the quantity and irradiation of fuel processed. Similarly, the dose to the population would depend on the population distribution around a specific plant. Taking the estimates of average concentrations per unit rate of discharge as a function of distance given by Bryant (85), and a uniform density of 100 persons per square kilometre, the population gonad dose commitment is 5.4 10^{-3} man-rad (MW(e) y)$^{-1}$ to the population (about 20 million) living within 250 kilometres of the site (table 74).

(c) *Dose to local populations due to other airborne radio-nuclides*

393. The concentrations of ^{90}Sr in milk from farms about five kilometres from the Windscale plant are not significantly different from those expected (typically 15 pCi (gCa)$^{-1}$) from the fall-out from weapons tests (654). Somewhat higher levels (about 40 pCi (gCa)$^{-1}$) have been found at farms nearer the site but these are believed to be due to the ^{90}Sr deposited as a result of discharges from the experimental reactors at Windscale during their early years of operation (414).

394. Levels of ^{90}Sr and ^{137}Cs in the diet, excluding fish and deer caught locally, of persons living near the NFS plant in New York State cannot be distinguished from those observed elsewhere in the state which arise from the fall-out from nuclear weapons tests.

395. Doses to individuals living near the reprocessing plants, resulting from discharges of ^{3}H to the atmosphere, can be calculated using methods similar to those used to estimate corresponding doses

from ^{85}Kr. Thus, taking the ^{3}H production rate of a thermal reactor to be 21 Ci (MW(e) y)$^{-1}$ (table 55), the average from a plant handling fuel at the annual rate equivalent to 1 MW(e) y is 6.3 10^{-9} Ci s^{-1} assuming that 1 per cent of the total ^{3}H is discharged to the atmosphere (paragraph 379). At a long-term concentration of 10^{-7} Ci m^{-3} per Ci s^{-1} discharged (paragraph 392), the concentration in ground-level air within a few kilometres of the plant would be 6.3 10^{-4} pCi m^{-3} and the annual dose to the persons exposed 6.3 10^{-10} rad (MW(e) y)$^{-1}$. For the population within 250 kilometres of the site as previously described the corresponding population dose commitment is about 10^{-4} man-rad (MW(e) y)$^{-1}$ (table 74).

(d) *Doses to the world population resulting from ^{85}Kr and ^{3}H discharged by the nuclear power industry*

396. Since the beginning of the nuclear era the concentration of ^{85}Kr in the atmosphere has steadily increased (figure XXXII) from 0 to about 15 pCi m^{-3} in 1970 in the middle latitudes of the northern hemisphere (45, 130, 142, 153, 154, 327, 476, 477, 545, 560, 561). From experimental results of the distribution of ^{85}Kr throughout the troposphere (figure XXXIII) the Committee has calculated that a world-wide average concentration at sea level of 4.6 pCi m^{-3} corresponds to the cumulative amount of ^{85}Kr in the world in 1970 due to nuclear power production (19 MCi, table 55). The average concentration due to the discharge of 510 Ci (MW(e) y)$^{-1}$, would, therefore, be about 1.2 10^{-4} pCi m^{-3}. But a ^{85}Kr concentration of 1 pCi m^{-3} delivers 1.7 10^{-8} rad y^{-1} to the gonads (table 22), so that the gonad dose commitment resulting from generation of one megawatt-year of electricity by a thermal reactor is 3.1 10^{-11} rad (MW(e) y)$^{-1}$ (table 74). The gonad dose commitment per year of generation of electricity at the 1970 rate is thus about 3 10^{-7} rad. In the year 2000, because of the large proportion of fast reactors, the dose commitment per unit of power generated given above does not apply. The gonad dose commitment per year of generation of electricity at the rate estimated for the year 2000 has been calculated from the ratio of the annual production of ^{85}Kr in the years 2000 and 1970 given in table 55 and has been found to be 4.5 10^{-5} rad.

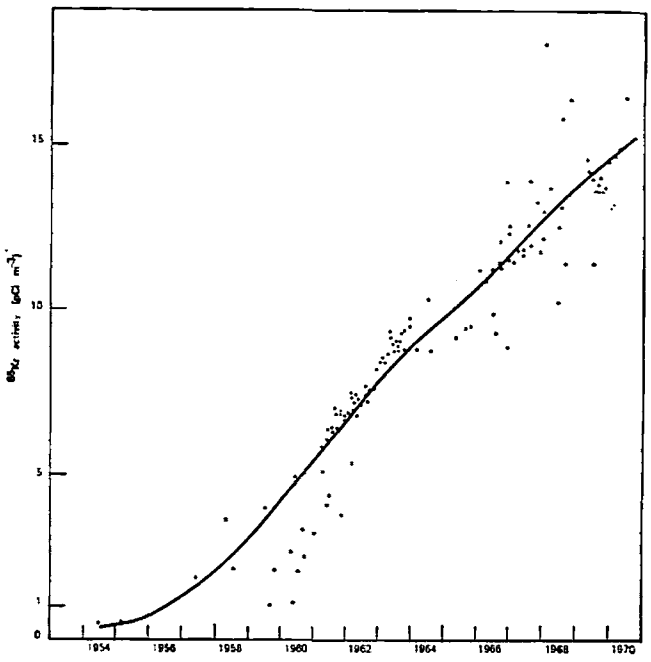


Figure XXXII. Activity of ^{85}Kr in northern hemisphere air samples (45, 130, 142, 153, 154, 327, 476, 477, 545, 560, 561)

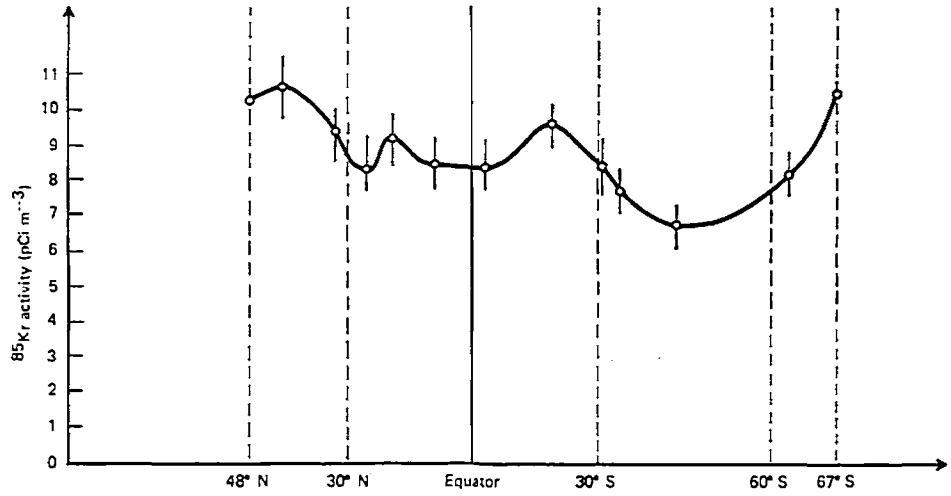


Figure XXXIII. Activity of ^{85}Kr in ground-level air as a function of latitude at the end of 1964 (476)

397. From the relationship that 1,900 MCi ^{3}H produced in weapons tests up to 1963 gives rise to a dose commitment of 4 10^{-6} rad (paragraph 166) and the value of 21 Ci ^{3}H per MW(e) y discharged (table 55), gonad dose commitments can be calculated in the same way as for ^{85}Kr. The results are given in table 74.

H. Summary of doses from the nuclear power industry

398. The preceding paragraphs and table 75 contain the results of the Committee's first attempt to assess the dose commitments associated with the nuclear power industry, which, in several countries, is now a firmly based and expanding commercial undertaking. The information available relates for the most part to special groups within populations, which, by virtue of place of residence or living habits, are expected to receive the greatest doses.

399. The population dose to defined groups has been given in those cases where the numbers of persons receiving the estimated dose commitments are known. In many instances, however, it has not been possible to calculate the additional component of the dose commitment relevant to the world population although this has been done for the important cases of the discharge to atmosphere of ^{85}Kr and ^{3}H from reprocessing plants.

400. In some cases, the dose commitments and associated population dose commitments to defined groups are overestimates because they include the dose contribution from fall-out from nuclear weapons testing. Since the fraction due to this cause is usually unknown it cannot be subtracted from the estimate of the gross dose commitment.

401. The amounts of radio-nuclides discharged to the environment and also the dose commitments per unit of electricity generated have, on average, decreased during the past several years due to improvements in technology and operating practices in existing and new reactors. Since there is reason to suppose that these improvements will continue to be made, extrapolating the dose commitments given in this report to future power production is not necessarily valid.

402. The discharge of long-lived radio-nuclides to the environment carries a dose commitment to the worldwide population. In the important cases of ^{3}H and ^{85}Kr the Committee has estimated the magnitude of the global dose commitment. The global doses from ^{85}Kr and ^{3}H per unit of power generated are at present about 10^{-1} man-rad $(MW(e)\ y)^{-1}$ and by the year 2000, on the basis of an installed power of 4,300 GW(e) at a load factor of 0.5, the dose commitment incurred per year of power generation would then represent only about 0.2 per cent of that due to natural background, even if the methods at present available for restriction of these releases are not by that date widely applied.

403. In the case of other long-lived radio-nuclides such as ^{137}Cs and ^{90}Sr the data available relate specifically to the immediate environs of the plants. Table 75 gives the dose commitments to persons living there from ^{137}Cs and other nuclides per megawatt-year of power generated. For the power-generating plants even of substantial sizes, the dose commitments from these nuclides and also from the shorter-lived noble gases correspond to individual dose rates of only a few millirads per year which may be compared with the natural background dose rate of about 100 millirads per year. Increase in power production would tend to increase the numbers of persons involved as more plants come into operation so that while the individual doses may not change much, the population dose commitment would rise with increasing installed power. However, even by the year 2000, this would still be extremely small.

404. In the case of the fuel-processing plants for which data are available, the individual dose rates at present are also similarly very small. It is difficult to predict the trend of events as the amount of fuel processing is increased. It seems likely that the doses in the vicinity of the plants will be kept to levels similar to current levels by regulatory control and that improved technology will be introduced so that this situation is maintained despite increased throughput.

III. Recapitulation of dose commitments

405. Table 76 summarizes the estimates of worldwide average dose commitments from all the considered sources of man-made environmental radiation. For underground testing and electric power production, the population dose commitments were divided by the world population to give the average individual dose commitments. For atmospheric testing, the estimates are the dose commitments for all tests conducted before 1971. Although it is acknowledged that the estimated doses from peaceful uses of explosives and production of electrical power are at this stage approximate, it is clear that the radio-active contamination of the environment is mainly the result of atmospheric testing.

406. The annual radiation exposures from natural background are also presented in table 76. The periods of time during which natural radiation would have to be doubled to give a dose increase equal to the total doses expected by the year 2000 from the current contamination of the environment are estimated to be of the order of two years for that due to the atmospheric tests carried out before 1971 and two hours for that due to the peaceful uses of explosives before 1972. Likewise, one year of electric power production at the 1970 rate and at the assumed 2000 rate would involve doses corresponding to about five minutes and one day of natural background, respectively.

TABLE I. COMPOSITION OF PRIMARY GALACTIC COSMIC RAYS AT 51° N IN 1952 AND 1954 (197)

Atomic number	*Vertical flux density (particles $m^{-2}\ sr^{-1}\ s^{-1}$)*
1	1,300
2	88
3-5	1.9
6-9	5.7
10-19	1.9
20 or more	0.5

TABLE 2. PROPERTIES OF SOME COSMIC-RAY PARTICLES PRESENT IN THE EARTH'S ATMOSPHERE (159)

Class	Name		Mass (MeV)	Mean life (s)	Principal mode of decay
Hadrons					
Nucleons	Proton	(p)	938.2	Stable	Stable
	Neutron	(n)	939.5	1.01 10^{3}	$p + e^{-} + \nu_e$
Mesons	Pion	($\pi^{\pm}$)	139.6	2.55 10^{-8}	$\mu + \nu_\mu$
		(π^{0})	134.9	1.78 10^{-16}	$\gamma + \gamma$
	Kaon	($K^{\pm}$)	493.7	1.23 10^{-8}	$\mu + \nu_\mu$
		(K_1)	497.7	0.91 10^{-10}	$\pi + \pi^{-}$
		(K_2)	497.7	5.7 10^{-8}	$\pi + e + \nu_e$
Leptons					
	Muon	($\mu^{\pm}$)	105.6	2.2 10^{-6}	$e^{\pm} + \nu_e + \nu_\mu$
	Electron	($e^{\pm}$)	0.511	Stable	Stable
	Neutrino	(ν_e)	0	Stable	Stable
		(ν_μ)	0	Stable	Stable
Photons	Photon	(γ)	0	Stable	Stable

TABLE 3. ABSORBED DOSE RATES PER NEUTRON CM^{-2} S^{-1} FOR SEA-LEVEL COSMIC-RAY NEUTRONS INCIDENT UPON A 30-CM TISSUE-EQUIVALENT SLAB, AND ASSOCIATED QUALITY FACTORS (219)

	Monolateral		Bilateral	
Depth (cm)	μrad h^{-1}	quality factor	μrad h^{-1}	quality factor
	Normal incidence			
Surface	9.1	10.0	6.5	8.2
5	8.2	7.7	6.2	6.7
0-15[a]			6.3	7.2
	Isotropic incidence			
Surface	8.2	8.3	5.4	7.1
5	6.1	5.5	4.6	4.7
0-15[a]			4.9	6.0

[a] For a 30-cm diameter cylinder. The mean is weighted proportionally to the radius.

TABLE 4. SUMMARY OF SEA-LEVEL COSMIC-RAY NEUTRON DATA

(Average dose rates in a 30-cm cylinder)

North latitude (degrees)	Flux density (n cm^{-2} s^{-1})	Dose rate (mrad y^{-1})[a]	Reference
41	0.01	0.43	615
54	0.0065	0.28	468
46	0.0065	0.28	64
46	0.0180[b]	0.77	65
55	0.0180[c]	0.77	642
46	0.0084	0.36	325
44	0.0074	0.32	659
41	0.0082	0.35	219

[a] The quality factor of this radiation is 6.
[b] Obtained by Watt (642) extrapolating higher altitude data to the sea level using 145 g cm^{-2} relaxation length.
[c] Average value from several investigators' results, as extrapolated.

TABLE 5. DOSE RATES TO PERSONS IN CONVENTIONAL JETS AND IN SST AIRCRAFT ASSUMED TO FLY IN POLAR REGIONS[a]

Altitude (km)	Dose rates (μrad h⁻¹)[b]			
	Galactic ionizing component[c]	Galactic neutron component[c]	Galactic star component[d]	Solar radiation (average)[e]
12	300	20		4
20	600	30	64	90

[a] If the flight altitude is less than 20 km and the latitude is lower, the dose rates for SST flights will also be lower.

[b] These radiations do not have the same quality factor. See table 3.

[c] Taken from figure VI. Data corresponding to solar minimum. At solar maximum the dose rates would be reduced by a factor of about 2.

[d] Taken from reference 185.

[e] Taken from reference 267.

TABLE 6. COSMIC RAY PRODUCED RADIO-ACTIVE NUCLIDES (348)

Radio-nuclide	Calculated atmospheric production rate (atoms cm⁻² s⁻¹)	Half-life	Maximum energy of beta radiation (keV)
^{3}H	0.20[a]	12.3 y	18
^{7}Be	$8.1\ 10^{-2}$	53 d	Electron capture
^{10}Be	$4.5\ 10^{-2}$	$2.5\ 10^{6}$ y	555
^{14}C	2.5	5,730 y	156
^{22}Na	$8.6\ 10^{-5}$	2.6 y	545 (β^+)
^{24}Na	$3.0\ 10^{-5}$	15.0 h	1,389
^{28}Mg	$1.7\ 10^{-4}$	21.2 h	460
^{26}Al	$1.4\ 10^{-4}$	$7.4\ 10^{5}$ y	1,170
^{31}Si	$4.4\ 10^{-4}$	2.6 h	1,480
^{32}Si	$1.6\ 10^{-4}$	700 y	210
^{32}P	$8.1\ 10^{-4}$	14.3 d	1,710
^{33}P	$6.8\ 10^{-4}$	25 d	248
^{35}S	$1.4\ 10^{-3}$	87 d	167
^{38}S	$4.9\ 10^{-5}$	2.9 h	1,100
^{34m}Cl	$2.0\ 10^{-4}$	32.0 min	2,480
^{36}Cl	$1.1\ 10^{-3}$	$3.1\ 10^{5}$ y	714
^{38}Cl	$2.0\ 10^{-3}$	37.3 min	4,910
^{39}Cl	$1.4\ 10^{-3}$	55.5 min	1,910
^{39}Ar	$5.6\ 10^{-3}$	270 y	565
^{81}Kr	$1.5\ 10^{-7}$	$2.1\ 10^{5}$ y	Electron capture

[a] Taken from reference 604.

TABLE 7. SOME NON-SERIES PRIMORDIAL RADIO-ISOTOPES (516, 615)

Radio-nuclide	Abundance in the lithosphere (ppm)	Half-life (years)	Alpha or maximum beta ray energy (keV)[a]	Gamma ray energies (keV)[a]
^{40}K	3	$1.3\ 10^{9}$	β 1,314 (89)	1,460 (11)
^{50}V	0.2	$6\ 10^{15}$	β ? (30)	783 (30), 1,550 (70)
^{87}Rb	75	$4.8\ 10^{10}$	β 274 (100)	
^{115}In	0.1	$6\ 10^{14}$	β 480 (100)	
^{138}La	0.01	$1.1\ 10^{11}$	β 210 (30)	810 (30), 1,426 (70)
^{147}Sm	1	$1.1\ 10^{11}$	α 2,230 (100)	
^{176}Lu	0.01	$2.2\ 10^{10}$	β 430 (100)	88 (15), 202 (85), 306 (95)

[a] Figures in parentheses indicate percentage yield per disintegration.

TABLE 8. ANNUAL INTERNAL BETA AND GAMMA DOSES FROM NATURALLY OCCURRING RADIO-NUCLIDES (mrad)

Radio-nuclide	Gonads	Cortical bone		Trabecular bone	
		Osteocytes	Haversian canals	Surfaces[a]	Marrow
^{3}H	~0.001	~0.001	~0.001	~0.001	~0.001
^{14}C	0.7	0.8	0.8	0.8	0.7
^{40}K	19	6	6	15	15
^{87}Rb	0.3	0.4	0.4	0.6	0.6
TOTAL	20.0	7.2	7.2	16.4	16.3

[a] Cells close to surfaces of bone trabeculæ.

TABLE 9. ANNUAL ALPHA DOSES (mrad) FROM NATURALLY OCCURRING RADIO-NUCLIDES CALCULATED BY THE METHOD OF SPIERS (577)

Radio-nuclide	Location	Activity in bone[a] (pCi kg^{-1})	Doses				
			Gonads	Cortical bone		Trabecular bone	
				Osteocytes	Haversian canals[b]	Surfaces[c]	Marrow
^{238}U	Normal areas (U.S.A., U.K.)	4.5	0.03	0.8	0.5	0.3	0.06
^{226}Ra	Normal areas (average)	7.6	0.02	1.6	1.0	0.6	0.1
	India (Kerala State)	77	0.2	16.0	9.8	6.6	1.2
	Brazil (Araxa-Tapira region)	46	0.1	9.5	5.8	3.9	0.7
^{228}Ra	Normal areas (average)	3.8	0.03	1.9	1.1	0.8	0.1
^{222}Rn[d]	Normal areas (continents)		0.07	0.04	0.04	0.08	0.08
^{220}Rn[d]	Normal areas (continents)		0.003	0.02	0.02	0.05	0.05
^{210}Po	Normal areas (northern temperate latitudes)	40	0.6	4.0	2.4	1.6	0.3
	Arctic regions[e]	100	7.2	10.0	6.0	4.0	0.7
	TOTAL FOR NORMAL AREAS	55.9	0.7	8.4	5.1	3.4	0.7

[a] The total mass of bone (defined as calcified matrix) in man has been taken to be 5,000 grammes yielding 1,000 grammes of calcium and 2,700 grammes of ash (see reference 401 and paragraphs 80 and 205). The alpha-emitting radio-nuclides were assumed to be uniformly distributed in mineral bone, although that may not be the case (269).

[b] Cells lining surfaces of Haversian canals.

[c] Cells close to surfaces of bone trabeculæ (averaged dose over the first 10 μm).

[d] Doses extrapolated from experiments in guinea-pigs. Other assumptions are given in table 16.

[e] Calculated from an arctic/non-arctic ^{210}Po concentration ratio of 2.5 in bone and 12 in soft tissue.

TABLE 10. ESTIMATES OF TOTAL INTAKE OF ^{226}Ra AND OF ^{228}Ra CONTRIBUTIONS FROM DIFFERENT FOOD-STUFF CATEGORIES

	Areas of normal external radiation background											*Area of high external radiation background*	
	^{226}Ra									^{228}Ra		^{226}Ra	^{228}Ra
		France	*India*		*Union of Soviet Socialist Republics*	*United Kingdom*	*United States*			*United States*		*India*	
	Argentina (48)	*Paris (550)*	*Bombay (110)*	*Tarapur (309)*	*Large town in central Asia (676)*	*County-wide study (570)*	*New York (173)*	*San Francisco (173)*	*San Juan (220)*	*New York (508)*	*San Francisco (508)*	*Kerala (110)*	*Kerala (424)*
Cereals and grain products	0.20		0.42	0.39	3.60[a]	0.17	0.56	0.39		0.42	0.37	1.48	3.23
Meat, fish, eggs	0.14		0.05	0.08	0.66	0.38	0.46	0.07		0.14	0.08	0.50	62.70
Milk and dairy products	0.05		0.04	0.01	0.98	0.14	0.14	0.05		0.05	0.10	0.19	15.30
Green vegetables, fruits and pulses	0.23		0.17[b]	0.05	2.70[c]	0.32	0.54	0.24		0.44	0.38	0.81	9.17
Root vegetables	0.14					0.10	0.06	0.04		0.12	0.08		29.58
Water			0.06	0.02	8.8	0.07	0.02	0.03				0.29	0.01
Miscellaneous	0.01		0.02									0.07	42.50
Total (pCi d^{-1})	0.8	1.1	0.8	0.5	17	1.2	1.8	0.8	0.7	1.2	1.0	3.3	160
Total (pCi $(gCa)^{-1}$)	1.1	1.1	1.6	1.0	17	1.1	1.8	0.8	1.3	1.2	1.0	6.6	320

[a] Bread only.
[b] Vegetables, fruits and pulses.
[c] Vegetables and fruits.

TABLE 11. ^{226}Ra IN HUMAN BONE

Location	Number of samples	Mean concentration in bone ash ($fCi\ g^{-1}$)	Reference
Normal areas			
Argentina: 1	18	11	641
2	360	12	48
Australia	22	10	641
Canada	12	6	641
Chile	24	4	641
Congo	14	22	641
Federal Republic of Germany	22	13	582
Guatemala	29	5	641
India (Bombay): 1	12	8	641
2	1	8	110
Israel	13	36	641
Japan	36	4	641
South Africa	13	11	641
United Kingdom	21	15	641
United States:			
Boston	77	14	641
Houston	23	23	641
Illinois	128	37	249
New England: 1	18	16	57
2	218	16	256
New York: 1	143	10	641
2		13	173
Puerto Rico: 1	42	5	641
2		6	220
San Francisco		11	173
Wisconsin	75	12	403
Union of Soviet Socialist Republics (Ukraine)		39	440
High-level areas			
India (Kerala)	1	143	110
Union of Soviet Socialist Republics (large town in central Asia)	282	1,340	676

TABLE 12. MEAN ^{222}Rn CONCENTRATIONS IN EQUILIBRIUM WITH SHORT-LIVED DECAY PRODUCTS IN GROUND-LEVEL AIR

Site	*^{222}Rn activity ($pCi\ l^{-1}$)*	*Reference*
Continental		
Czechoslovakia		
Bratislava	0.14	662
Hungary		
Budapest	0.07	564
USA		
Chicago	0.03	60
Cincinnati	0.26	203
USSR		
Moscow	0.07	397
Coastal areas and islands		
American Samoa	0.001	60
Bolivia		
Chacaltaya	0.04	370
Brazil		
Rio de Janeiro	0.05	370
Japan	0.09	442
Morocco		
Kenitra	0.008	60
Peru		
Lima	0.04	370
Philippines		
Luzon	0.004	60
USA		
Kodiak	0.003	60
Oahu	0.001	60
Washington, D.C.	0.12	370
Areas of negligible exhalation rate		
Antarctic Ocean	0.001	549
Indian Ocean	0.002	549
North Atlantic Ocean	0.006	549
South Pacific Ocean	0.002	549
South Pole	0.0005	370

TABLE 13. ^{222}Rn CONCENTRATION IN DWELLINGS

Location	Number of buildings investigated	Type of building and building material	^{222}Rn concentration outdoors (pCi l^{-1}) Range	^{222}Rn concentration outdoors (pCi l^{-1}) Mean	^{222}Rn concentration indoors (pCi l^{-1}) Range	^{222}Rn concentration indoors (pCi l^{-1}) Mean	Comments	Reference
Poland	28	Apartments — Concrete	0.06–0.16	0.11	0.14–2.14	0.44	Measurements made under similar conditions of ventilation	498
	8	Aggregate	0.06–0.09	0.08	0.26–1.10	0.35		
	6	Brick			0.08–0.37	0.19		
Sweden	55	Houses — Wood			0.3–0.9	0.54	Four air changes per hour	255
	87	Brick			0.3–2.1	0.91		
	83	Concrete (including alum shale)			0.3–4.5	1.86		
Union of Soviet Socialist Republics		Silicate brick			0.12–4.3			680
		Red brick			0.19–1.10			
		Concrete			0.4			
		Adobe			0.3-10.0			
		Slag			4.0-8.0			
United Kingdom	1	House		0.04	0.06–0.31	0.16	Adequately ventilated	227
	1	House		0.13	0.2–0.7	0.4	Inadequately ventilated	
	6	Industrial premises	0.04–0.19	0.09	0.005–1.2	0.3	Poor ventilation	
	4	Office buildings		0.04	0.06–0.35	0.17	Air conditioned	
United States of America:								
Boston area	7	One-family houses:	0.01–0.15	0.05			Number of air changes per hour: one to three in the basement, two to six on the first floor	660
		first floor (wood frame)			0.005–0.23	0.07		
		basement (concrete)			0.1–0.94	0.40		
	3	Apartments — Brick			0.01–0.19	0.09	Number of air changes per hour: five to nine	660
	4	Offices and laboratories			0.02–0.10	0.05	Number of air changes per hour: five to twelve. Air conditioned buildings	660
Tennessee	15	Houses — most of them of concrete construction			0.13–4.8[a]	1.40	The ventilation rate was probably higher in Florida than in Tennessee as the outdoors temperatures were respectively, 23° C and 0° C	377
Florida	16				0.03–3.6[a]	1.26		377
New York				0.13		0.25		377

[a] Converted from working level units by assuming that ^{222}Rn and its daughters are in the equilibrium ratio 1/0.9/0.6/0.4.

TABLE 14. AIRWAY CHARACTERISTICS OF WEIBEL'S LUNG MODEL A (REGULAR DICHOTOMY) (238, 644)

Region	*Generation*	*Number*	*Radius (cm)*	*Length (cm)*	*Mucus transit time (min)*
Trachea	0	1	0.9000	12.0	8
Main bronchi	1	2	0.6100	4.76	6
Secondary bronchioles	2	4	0.4150	1.90	8
	3	8	0.2800	0.76	3
Tertiary bronchioles	4	16	0.2250	1.27	14
	5	32	0.1750	1.07	12
	6	64	0.1400	0.90	10
Quarternary bronchioles	7	128	0.1150	0.76	32
	8	256	0.0930	0.64	27
	9	512	0.0770	0.54	23
Terminal bronchioles	10	1,024	0.0650	0.46	445
	11	2,048	0.0545	0.39	378
	12	4,096	0.0475	0.33	320
	13	8,192	0.0410	0.27	261
	14	16,384	0.0370	0.23	223
	15	32,768	0.0330	0.20	194
	16	65,536	0.0300	0.165	160
Respiratory bronchioles	17	131,072	0.0270	0.141	
	18	262,144	0.0250	0.117	
	19	524,288	0.0235	0.099	
Alveolar ducts	20	1,048,576	0.0225	0.083	
	21	2,097,152	0.0215	0.070	
	22	4,194,304	0.0205	0.059	
Alveolar sacs	23	8,388,608	0.0205	0.050	
Alveoli			~0.02		

TABLE 15. CALCULATED ALPHA DOSE RATES FROM INHALATION OF SHORT-LIVED ^{222}Rn DAUGHTER PRODUCTS TO THE BASAL CELL NUCLEI OF SEGMENTAL BRONCHI (226)

	Depth (μm)				
	15	*30*	*45*	*60*	*70*
Living accommodation: adequate ventilation[a]	550	280	100	40	1.5
Living accommodation: inadequate ventilation[b]	1,490	790	330	120	5
Industrial premises[c]	840	445	190	75	3
Air-conditioned sites[d]	280	140	50	15	0.6

[a] ^{222}Rn, ^{218}Po, ^{214}Pb and ^{214}Bi concentrations: 0.164, 0.148, 0.083 and 0.057 pCi l^{-1} respectively. Annual dose (6,000 h) in millirads.

[b] ^{222}Rn, ^{218}Po, ^{214}Pb and ^{214}Bi concentrations: 0.37, 0.35, 0.26 and 0.21 pCi l^{-1} respectively. Annual dose (6,000 h) in millirads.

[c] ^{222}Rn, ^{218}Po, ^{214}Pb and ^{214}Bi concentrations: 0.32, 0.31, 0.27, 0.25 pCi l^{-1} respectively. Annual dose (2,000 h) in millirads.

[d] ^{222}Rn, ^{218}Po, ^{214}Pb and ^{214}Bi concentrations: 0.17, 0.15, 0.074, 0.060 pCi l^{-1} respectively. Annual dose (2,000 h) in millirads.

TABLE 16. ESTIMATED ANNUAL ALPHA DOSES (mrad) IN HUMAN ORGANS RESULTING FROM INHALATION OF RADON DAUGHTERS WITH A MEAN ASPIRATION RATE OF 13.9 LITRES PER MINUTE (511)

	^{222}Rn concentration 0.3 pCi l^{-1} (^{222}Rn and daughters in the ratio 1/0.8/0.4/0.3)	^{212}Pb concentration 3 fCi l^{-1} (^{212}Pb-^{212}Bi in equilibrium)
Lungs (alveolar tissue)	2.2	0.6
Blood	0.2	0.1
Liver	0.1	0.07
Kidneys	0.5	0.2
Adrenal glands	0.1	0.02
Muscle	0.05	0.003
Bone	0.04	0.02
Bone marrow	0.08	0.05
Gonads	0.07	0.003

TABLE 17. DIETARY INTAKE OF ^{210}Pb AND ^{210}Po IN SOME COUNTRIES

Country	Dietary intake (pCi d^{-1}) ^{210}Pb	Dietary intake (pCi d^{-1}) ^{210}Po	Reference
Areas of normal dietary intake			
Argentina		1.3	45
Federal Republic of Germany	4.6	4.6	200
Union of Soviet Socialist Republics (Leningrad)	4	3.0	664
United Kingdom	1-10	1-10	247
United States of America:			
Palmer, Alaska	1.7		391
Los Angeles, California	1.5		
Honolulu, Hawaiian Islands	1.6		
Chicago, Illinois	1.8		
New Orleans, Louisiana	1.8		
Boston, Massachusetts	1.7		
New York City, New York	1.2		437
Areas of high dietary intake			
Finland (Lapps)	8.6	69	317
Japan	17		599

TABLE 18. MEASURED DOSE RATES IN AIR FROM TERRESTRIAL GAMMA RADIATION IN SELECTED AREAS (mrad y^{-1})

Country	Area	Outdoors: No. of sites	Outdoors: Range	Outdoors: Mean	Indoors: No. of sites	Indoors: Range	Indoors: Mean	Reference
Egypt				52			49	483
Federal Republic of Germany		27,000 km of roads		34	2,000		70	193
Finland		11		86	11	59-142	82	281
German Democratic Republic	Country-wide	1,097	15-400	82	607	30-230	64	470
Italy	Rome	78	91-250	181	15	90-230	162	102
Japan[a]		225	0-83	42				8, 9, 10
New Zealand	Dunedin			37			37	287
Poland	Country-wide	16	20-113	51		49-76	60	497
Sweden	Lapp communities	5	43-69	53	9	50-60	53	217
Union of Soviet Socialist Republics					33	25-168	66	680
United Kingdom	Aberdeenshire	217	34-103	70	172	51-118	82	579
United States	Country-wide	>200	25-100	55			38	37

[a] These figures obtained by subtracting 30 mrad y^{-1} as estimated cosmic-ray contribution

TABLE 19. DOSE CONVERSION FACTORS: GONADS/AIR (49, 297)

Radio-nuclide	Distribution in soil	Results of Bennett			Results of Jones		
		Testes	Ovaries	Mean	Testes	Ovaries	Mean
^{238}U series	Uniform	0.85	0.75	0.80	0.87	0.74	0.80
^{232}Th series	Uniform	0.86	0.76	0.81	0.87	0.75	0.81
^{40}K	Uniform	0.87	0.79	0.83	0.85	0.73	0.79
^{137}Cs	Plane	0.88	0.80	0.84	0.83	0.69	0.76
^{137}Cs	Exponential	0.87	0.77	0.82	0.84	0.71	0.77

TABLE 20. DOSE RATES DUE TO INTERNAL AND EXTERNAL IRRADIATION FROM NATURAL SOURCES IN "NORMAL" AREAS. ESTIMATES OF THE 1966 REPORT ARE GIVEN IN PARENTHESES.

Source of irradiation	Dose rates (mrad y^{-1})					Paragraph
	Gonads		Bone-lining cells	Bone marrow		
External irradiation						
Cosmic rays: ionizing component	28	(28)	28	28	(28)	41
neutron component	0.35	(0.7)	0.35	0.35	(0.7)	46
Terrestrial radiation (including) air	44	(50)	44	44	(50)	145
Internal irradiation						
^{3}H	0.001	(—)	0.001	0.001	(—)	62
^{14}C	0.7	(0.7)	0.8	0.7	(1.6)	67
^{40}K	19	(20)	15	15	(15)	72
^{87}Rb	0.3	(0.3)	0.6	0.6	(<0.3)	73
^{210}Po	0.6	(0.3)	1.6	0.3	(0.3)	131
^{220}Rn	0.003	(—)	0.05	0.05	(—)	119
^{222}Rn	0.07	(0.3)	0.08	0.08	(0.3)	118
^{226}Ra	0.02	(—)	0.6	0.1	(0.03)	92
^{228}Ra	0.03	(—)	0.8	0.1	(0.03)	92
^{238}U	0.03	(—)	0.3	0.06	(—)	80
ROUNDED TOTAL	93	(100)	92	89	(96)	
Percentage from alpha particles plus neutrons	1.2	(1.3)	4.1	1.2	(1.4)	

TABLE 21. INITIAL VERTICAL DISTRIBUTION OF RADIO-ACTIVITY ASSUMED WITHIN "MUSHROOM CAP" OF THE CLOUD FROM A NUCLEAR EXPLOSION (506)

Layer, fraction of "mushroom cap" (from base to top)	Percentage of activity within layer
$0 — \frac{1}{7}$	1
$\frac{1}{7} — \frac{2}{7}$	14
$\frac{2}{7} — \frac{3}{7}$	25
$\frac{3}{7} — \frac{4}{7}$	25
$\frac{4}{7} — \frac{5}{7}$	15
$\frac{5}{7} — \frac{6}{7}$	15
$\frac{6}{7} — \frac{7}{7}$	5

TABLE 22. ANNUAL DOSES RECEIVED BY AN INDIVIDUAL EXPOSED TO AN ACTIVITY CONCENTRATION OF 1 pCi m^{-3} OF ^{85}Kr

Organs and tissues	*Annual dose (nrad)*	*Reference*
Lung	32	648
Tracheal mucosa	52	648
Fatty tissue	2	610
Blood	0.2	610
Muscle	0.2	610
Skin	2,100	149
Subcutaneous tissue	51	610
Gonads	17	149
Entire body	14	149

TABLE 23. ^{90}Sr INVENTORY IN MEGACURIES (340, 343, 344, 385, 616, 632, 635)

	1967				*1968*				*1969*			*1970*				*1971*
	Jan.	*Apr.*	*July*	*Oct.*	*Jan.*	*Apr.*	*June*	*Oct.*	*Feb.*	*Apr.*	*July*	*Jan.*	*May*	*Aug.*	*Nov.*	*Feb.*
Stratosphere ...	0.3	0.3	0.3	0.4	0.3	0.2	0.2	0.4	0.4	0.3	0.2	0.4	0.3	0.3	0.4	0.5
Troposphere ...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Local fall-out ..	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.0	2.0	2.0	2.0	1.9	1.9	1.9	1.8	1.8
Global fall-out .	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.1	12.2	12.1	12.1	12.2	12.2	12.2
TOTAL	14.6	14.6	14.6	14.7	14.6	14.5	14.5	14.6	14.6	14.4	14.4	14.4	14.3	14.4	14.4	14.5

TABLE 24. ANNUAL AND CUMULATIVE WORLD-WIDE ^{90}Sr DEPOSITION (MCi) (634)

	Annual deposition			*Cumulative deposit*		
	Northern hemisphere	*Southern hemisphere*	*Global*	*Northern hemisphere*	*Southern hemisphere*	*Global*
Pre-1958	1.80[a]	0.65[a]	2.45[a]	1.7	0.6	2.3
1958	0.63	0.25	0.88	2.28	6.84	3.12
1959	1.05	0.18	1.23	3.26	1.00	4.26
1960	0.26	0.17	0.43	3.44	1.14	4.58
1961	0.35	0.17	0.52	3.70	1.29	4.99
1962	1.44	0.26	1.70	5.84	1.51	7.35
1963	2.62	0.31	2.93	7.51	1.78	9.29
1964	1.65	0.42	2.07	8.96	2.16	11.12
1965	0.77	0.36	1.13	9.50	2.46	11.96
1966	0.32	0.21	0.53	9.59	2.68	12.27
1967	0.17	0.11	0.28	9.52	2.65	12.17
1968	0.19	0.10	0.29	9.48	2.69	12.17
1969	0.15	0.14	0.29	9.40	2.76	12.16
1970	0.21	0.13	0.34	9.37	2.82	12.19
TOTAL	11.61	3.46	15.07			
Stratospheric inventory	0.29	0.16	0.45			
All injections to 1970	11.90	3.62	15.52			

[a] Estimated from the cumulative deposition, assuming there had been a two-year decay.

TABLE 25. ACTIVITY OF ^{90}Sr IN RAIN (pCi l^{-1}) AND WET DEPOSITION (mCi km^{-2}) (101, 230, 231)

	1965		1966		1967		1968		1969		1970	
	pCi l⁻¹	*mCi km⁻²*	*pCi l⁻¹*	*mCi km⁻²*	*pCi l⁻¹*	*mCi km⁻²*	*pCi l⁻¹*	*mCi km⁻²*	*pCi l⁻¹*	*mCi km⁻²*	*pCi l⁻¹*	*mCi km⁻²*
1. *Continents*												
51° N Milford Haven	5.06	4.82	2.63	3.08	1.17	1.22	1.25	1.24	0.82	0.85	1.18	1.19
51° N Abingdon	5.49	3.09	2.40	1.78	1.30	0.78	1.20	0.91	1.34	0.81	0.96	0.57
40° N New York	8.35	5.53	2.40	2.43	1.31	1.64	1.14	1.32	1.16	1.43	1.65	1.48
25° N Miami	2.41	3.58	1.07	2.25	0.37	0.62	0.42	0.88	0.50	0.91	0.77	0.88
40° N Misawa	2.91	3.17	1.05	1.41	0.67	0.77	0.65	0.99	0.71	0.99	1.07	0.73
Mean	4.84	4.04	1.91	2.19	0.96	1.01	0.93	1.07	0.90	1.00	1.13	0.97
2. *Islands*												
21° N Honolulu	1.84	2.77	1.75	1.68	1.22	1.91	2.51	3.42	1.06	1.15	1.14	1.13
38° N Azores	2.08	2.84	1.35	2.14	0.43	0.54	0.27	0.33	0.50	0.53	0.96	1.30
32° N Bermuda	2.59	3.02	1.23	1.84	0.62	0.83	0.99	1.04	0.60	0.73	0.76	1.04
22° N Taiwan	0.99	1.18	1.68	0.29	0.10	0.17	0.07	0.20	0.08	0.15	0.09	0.18
Mean	1.87	2.45	1.50	1.49	0.59	0.86	0.96	1.25	0.56	0.64	0.74	1.22
3. *Ships*												
56° N Bravo	2.58	1.33	2.00	0.74	0.89	0.34	1.19	0.53	1.19	0.48	1.46	0.51
52° N Charlie	5.44	3.18	3.08	1.42	0.91	0.49	1.09	0.60	1.16	0.55	1.73	0.69
44° N Delta	2.80	2.25	2.42	1.59	0.80	0.66	1.01	0.81	0.83	0.63	0.87	0.71
35° N Echo	3.24	2.45	3.59	1.50	0.61	0.57	1.14	0.62	0.88	0.56	0.74	0.43
Mean	3.51	2.30	2.77	1.31	0.80	0.52	1.11	0.64	1.01	0.55	1.20	0.58

TABLE 26. LATITUDE POPULATION AND FALL-OUT DISTRIBUTION

Latitude	Area (10^6 km²)	Population (per cent)	Integrated deposit of ^{90}Sr (mCi km⁻²)[a] 1958-1970 (635)	Integrated deposit of ^{90}Sr (mCi km⁻²)[a] From all tests to 1970[b]	Integrated deposit of ^{90}Sr (mCi km⁻²) 1961-1969 (228)
70°-80° N	11.6		14.4	17.5	35
60°-70° N	18.9	0.4	37.2	45.2	217
50°-60° N	25.6	11.9	62.0	75.3	261
40°-50° N	31.5	17.7	68.9	83.7	346
30°-40° N	36.4	23.4	49.4	60.0	302
20°-30° N	40.2	25.2	38.3	46.5	229
10°-20° N	42.8	8.4	25.9	31.4	128
0°-10° N	44.1	4.0	16.9	20.5	117
0°-10° S	44.1	4.2	9.6	12.3	96
10°-20° S	42.8	1.7	8.2	10.5	36
20°-30° S	40.2	1.5	13.5	17.4	71
30°-40° S	36.4	1.4	14.5	18.6	43
40°-50° S	31.5	0.1	17.2	22.1	35
50°-60° S	25.6		9.6	12.3	

[a] The integrated deposit is sum of the activities deposited each month. There is no correction for radio-activity decay.

[b] The distribution of ^{90}Sr in the northern hemisphere for all injections up to 1970 is obtained by multiplying results in the previous column by 11.9/9.8, the ratio of the total deposition in the northern hemisphere for all injections to 1970 to that for the period 1958-1970 (see table 24). The data for the southern hemisphere are computed in like manner.

TABLE 27. POPULATION-WEIGHTED DEPOSITION OF STRONTIUM (mCi km⁻²)[a]

	^{90}Sr (1961-1969)	^{90}Sr (1958-1970)	^{90}Sr (All injections to 1970)
Northern hemisphere	260	48.1	58.4
Southern hemisphere	71	10.8	13.9
Global	243	44.8	54.4

[a] Estimated from data of table 26.

TABLE 28. ANNUAL DEPOSITION OF ^{89}Sr (MCi)[a]

	1961	1962	1963	1964	1965[b]	1966	1967	1968	1969
Northern hemisphere	8.1	27	15	0.35	—	0.67	0.57	0.74	0.56
Southern hemisphere	0.48	4.5	0.91	0	—	2.6	0.49	2.3	0.18

[a] Based upon measurements made at the United States fall-out sampling network (228).
[b] No results reported for 1965.

TABLE 29. ^{90}Sr AND ^{137}Cs IN MILK

Region or country	^{90}Sr to calcium ratio (pCi g^{-1})						^{137}Cs concentration (pCi l^{-1})						Reference
	1966	1967	1968	1969	1970	1971	1966	1967	1968	1969	1970	1971	
Northern hemisphere													
Austria	23	14	13	12			70	33	28	27			93, 94, 95, 653
Belgium	13	9	8	9	6		36	17	20	15	10		120, 551
Canada	13	10	8	9	9		51	33	25	20	21		136, 412, 515
Colombia	2	1	1		1								528
Czechoslovakia	12												441
Denmark	12	9	9	7	8	7	22	14	14	14	10	14	4, 5
Egypt	13		6										394, 395
Faroe Islands	73	51	45	35	37	34	800	586	507	463	357	352	4, 6
Federal Republic of Germany	16	11	9	9	7		61	35	27	25	31		91, 92
Finland	13	10	9	8			134	92	70	54	49		105
France: 1	19	14	12	9	8	9		21	20	19	21	22	186. 490. 550
2	18	15	12	12	12	11	62	34	24	24	26	28	123
Guiana	11	14			7								528
India (Bombay)							11	6	5				422, 423
Israel	2	2					14	11					170
Italy	13	10	8										119
Jamaica	9	7	4	4			200	184	109	95	81		621
Japan	11	8	7	5	5		52	30	28	18	16		19
Korea	22	11	15										335
Netherlands	15	9	8	7			43	37	28	23			120, 405, 460
Norway	28	16	11	10			244	181	146	128			260
Panama	4						21	22	11	11			621
Puerto Rico	6	4	4	4			21	14					621
Senegal	10	8	5		2								528
Sweden	15	10	8	7	7		63	38	30	20	23		218, 591
Switzerland	18	13	11	10	10		26	17	7	13	12		254
Union of Soviet Socialist Republics	12	8	8	7	7		56	38	30	20	20		671, 672, 681, 682
United Kingdom	12	9	8	7	6	6	46	20	16	14	17	18	11, 12
United States	12	9					29	16					621
Alaska	12	6	6	5			34	20	13				621
Chicago	9	8	8	6					14	16	14	14	74, 621
Hawaii	4	3	4	2			25	9					621
New York City	12	10	9	9	8	8							232
Tampa	11	11	7	5			139	102	66	55	51		521, 632
Venezuela	4						14	9					621
Southern hemisphere													
Argentina	5	5	4	4	3		24	21	19	20	20		118
Australia	7	5	4	5	6		28	20	15	18	19		23. 69, 177, 178, 194, 585
Chile	2	1	1										528
Ecuador	4	1	1		1								528
Malagasy Republic	2	2	1		2								528
New Caledonia	3	2	2		2								528
New Zealand	8	6	5	7	7		55	43	32	40	35		450
Peru	2	1	1										528
Réunion (La)		4	3	3	5			17	15	18	16		550
Society Islands	5	3	1		3								528

TABLE 30. 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				Mean
	Canada (136, 412, 515, 616)	Czechoslovakia (616)	Denmark (2, 4, 5)	Federal Republic of Germany (92)	Finland (105, 616)	France (490)	Netherlands (405, 460, 616)	Ukrainian SSR (678)	USSR Moscow (666, 672, 682)	United Kingdom (11, 12, 616)	Whole country	Chicago (232, 616, 621)	New York City (232, 616, 621)	Salt Lake City (232, 616, 621)	
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	8.6
1960			5	7	7				6	6		8	8	6	6.6
1961			4	6	6				4	6	7	6	7	4	5.6
1962			10	11	13		9		13	12	11	9	12	8	10.8
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	11	10	14	9		8	9	9	8	10	5	9.3
1968	8		9	9	9	12	8			8		8	9		8.9
1969	9		7	9	8	9	7			7		6	9		7.9
1970	9		8	7		8			6	6			8		7.4
1971			7			9				6			8		7.5

TABLE 31. ^{90}Sr AND ^{137}Cs IN TOTAL DIET

Region or country	^{90}Sr to calcium ratio ($pCi\ g^{-1}$)						^{137}Cs intake ($pCi\ d^{-1}$)						Reference
	1966	1967	1968	1969	1970	1971	1966	1967	1968	1969	1970	1971	
Northern hemisphere													
Austria	25	15	15	14			135	53	60	51			95
Denmark	14	10	8	8	7	7	79	44	39	38	32	34	4, 5
Egypt	45		13										394, 395
Faroe Islands	33	22	23	17	20		496	480	502	403	384		6
Federal Republic of Germany	17	13	11	10	9		123	77	43	37	30		92
Finland	21						260						259
France: 1	22	19	17	15	15	14							123
2			21	20	18	18			38	34	37	37	186, 490, 550
Greenland	15	9	7	8	6		89	297	346	61	137		7
Japan (urban)	24	18	19	21	15		20	14	13	14	9		20
Netherlands	20	14	12	11			90	50	32	28			460
Norway	38						420						259
Sweden	22						132	88	71	65	58		259, 390, 594
Union of Soviet Socialist Republics	40	28	25	19	20		145	93	56	38	38		671, 672, 681, 682
United States average	16	12					55	30	34	28	25	24	74, 214, 621
Alaska	29	16											621
Hawaii	10	6					65	35					621
New York City	17	16	14	12	12	13							51
San Francisco	6	6	4	4	4	4							51
Southern hemisphere													
Argentina	7	7	5	6	4			24	19	18	17		118
Australia	7	6	5	5	6								23, 177, 178, 194, 585

TABLE 32. RATIO OF $^{90}Sr/Ca$ IN WHOLE DIET TO THAT IN MILK[a]

Country	*1963*	*1964*	*1965*	*1966*	*1967*	*1968*	*1969*	*1970*	*Mean for 1963-1970*
Argentina	1.8	1.5	1.3	1.4	1.4	1.3	1.5	1.3	1.4
Australia	1.1	1.0	0.9	1.0	1.2	1.3	1.0	1.0	1.1
Denmark	1.3	1.7	1.3	1.2	1.1	0.9	1.1	0.9	1.2
Federal Republic of Germany	1.3	1.6	1.7	1.1	1.2	1.2	1.1	1.3	1.3
Finland			1.8	1.6					1.7
France				1.2	1.3	1.4	1.3	1.3	1.3
India				3.6					(3.6)
Japan	2.1	2.2	2.3	2.2	2.3	2.7	4.2	3.0	2.6
Norway			1.3	1.4					1.3
Sweden			1.4	1.5					1.4
United Kingdom	0.9	0.9	1.0						0.9
Union of Soviet Socialist Republics	2.3	3.1	3.7	3.3	3.5	3.1	2.7	2.9	3.1
United States, New York City	1.1	1.3	1.2	1.4	1.6	1.6	1.3	1.5	1.4
Hawaii	1.6	2.2	3.5	2.5	2.0				2.4

[a] Data taken from tables 29, 31 and from the 1969 report.

TABLE 33. PARAMETERS OBTAINED BY FITTING THE $^{90}Sr/Ca$ RATIO IN MILK TO THE ^{90}Sr DEPOSITION

	New York (eq. 15)	*Denmark (eq. 15)*	*United Kingdom (eq. 14)*	*United Kingdom (eq. 15)*	*Northern hemisphere[a] (eq. 15)*
p_1 (pCi (gCa)$^{-1}$ per mCi km^{-2} y^{-1})	0.69	0.99	0.70	0.86	0.86
p_2 (pCi (gCa)$^{-1}$ per mCi km^{-2} y^{-1})	0.21	0.47	1.41	0.47	0.48
p_3 (pCi (gCa)$^{-1}$ per mCi km^{-2} y^{-1})	0.20	0.25	0.21	0.11	0.20
μ (y^{-1})	0.14	0.15	0.18	0.08	0.10
P_{23} (pCi y (gCa)$^{-1}$ per mCi km^{-2})	2.23	3.01	2.33	2.65	3.24

[a] Calculated using data from table 30.

TABLE 34. $^{90}Sr/Ca$ RATIOS IN HUMAN BONE (pCi (gCa)$^{-1}$)

(Number of samples in parentheses)

Region or country	Year	New-born or stillborn	0-1 year	1 year	2 years	3 years	4 years	5-19 years	>19 years	Adult bone type[a]	Reference
					Northern hemisphere						
Canada	1968	3.2 (8)	4.1 (86)	4.8 (17)	4.3 (16)	4.4 (12)	5.8 (4)	3.8 (59)	2.7 (38)	V	603
	1969	2.5 (6)	4.0 (47)	5.0 (5)	5.1 (5)	4.4 (4)	4.2 (8)	3.3 (48)	2.2 (37)	V	603
Czechoslovakia	1966	2.2 (30)	3.3 (63)	3.5 (9)	3.3 (8)	3.8 (11)	3.0 (5)	2.9 (59)	1.8 (103)	V	75
	1967	1.6 (31)	2.8 (91)	4.1 (20)	3.8 (12)	2.9 (12)	2.9 (9)	2.8 (63)	1.9 (122)	V	75
	1968								1.7 (54)	V	76
	1969			3.2 (23)	2.3 (9)	2.8 (10)	3.0 (10)	2.4 (59)	1.8 (62)	V	78
	1970								1.7 (57)	V	79
Denmark	1969	1.2 (19)	1.7 (33)	2.4 (3)		2.1 (1)	1.8 (3)	1.9 (36)	1.3 (27)	V	5
	1970	0.9 (18)	1.9 (26)	1.9 (4)	1.9 (4)	1.7 (4)	0.8 (1)	1.5 (31)	1.3 (49)	V	5
	1971	1.2 (8)	1.7 (15)				1.4 (3)	2.0 (26)	1.8 (31)	V	4
Egypt	1968								0.4 (7)	V	396
	1969							0.1 (8)	0.2 (14)	V	396
Federal Republic of Germany	1968	1.2 (159)	2.4 (25)			2.8 (17)		2.5 (34)	1.8 (64)	V	92
	1969	1.1 (98)	1.9 (14)			2.3 (10)		2.0 (21)	1.7 (40)	V	92
France 1	1967	1.9 (5)	3.7 (53)	5.3 (10)	5.0 (5)		4.0 (1)	3.5 (41)	2.2 (55)	V	292
	1968	1.6 (60)	3.2 (102)	4.4 (13)	3.7 (9)	3.9 (4)	3.8 (6)	2.8 (38)	2.3 (88)	V	292
	1969	1.6 (25)	3.2 (87)	3.7 (15)	3.1 (12)	3.6 (5)	3.0 (6)	2.8 (54)	2.0 (105)	V	292
	1970	1.6 (37)	2.7 (73)	2.9 (15)	2.6 (11)	3.2 (6)	2.3 (15)	2.1 (42)	1.9 (132)	V	292
France 2	1967								1.7 (55)	Rib	490
	1968								1.0 (45)	Rib	490
	1969								1.3 (61)	Rib	490
	1970								1.2 (18)	Rib	490
Indonesia	1970								1.0 (6)	V	234
Jamaica	1970								0.9 (21)	V	234
Japan	1967		3.9 (2)	3.8 (2)	3.3 (2)	2.5 (1)	2.1 (1)	2.5 (21)	0.4 (1)	Composite	601
	1968	1.1 (12)	2.0 (31)	3.2 (10)	2.3 (4)	2.3 (3)	1.8 (3)	2.1 (47)	0.6 (13)	Composite	601
	1969	0.7 (30)	1.5 (15)	2.1 (5)	2.6 (7)	1.5 (7)	0.6 (1)	1.4 (26)	0.7 (12)	Composite	601
	1970	0.7 (23)			2.5 (1)		2.0 (3)	1.7 (14)	1.2 (6)	Composite	602

TABLE 34. $^{90}Sr/Ca$ RATIOS IN HUMAN BONE (pCi $(gCa)^{-1}$) (*continued*)

(*Number of samples in parentheses*)

Region or country	Year	New-born or stillborn	0-1 year	1 year	2 years	3 years	4 years	5-19 years	>19 years	Adult bone type[a]	Reference
					Northern hemisphere (continued)						
Senegal	1969								1.0 (12)	V	234
	1970								1.3 (24)	V	234
Switzerland	1970								2.5 (47)	V	254
Thailand	1970								0.7 (7)	V	234
	1971								0.6 (6)	V	234
Uganda	1970								1.1 (23)	V	234
Union of Soviet Socialist Republics	1968	1.7 (81)	2.4 (19)	———	———	3.0 (13)	———	2.2 (224)	1.2 (694)	Normalized to whole skeleton	674
	1969	1.5 (103)	2.1 (30)	———	———	3.1 (12)	———	2.0 (288)	1.2 (1,142)	Normalized to whole skeleton	675
	1970[b]	1.4 (81)	2.4 (32)	———	———	2.9 (35)	———	3.1 (329)	1.4 (1,249)	Normalized to whole skeleton	675
	1971[b]	1.0 (55)	2.3 (7)	———	———	2.5 (8)	———	2.7 (162)	1.3 (867)	Normalized to whole skeleton	675
United Kingdom	1968	1.3 (101)	2.9 (27)	3.2 (9)	2.7 (7)	3.4 (4)	2.7 (5)	1.9 (73)	1.6 (34)	Mainly vertebræ	415
United States: New York, N. Y.	1969		2.6 (23)	2.7 (1)	3.2 (2)	3.6 (1)	2.8 (2)	2.5 (29)	1.7 (25)	V	229
	1970		2.5 (12)	2.8 (1)		2.4 (1)		2.1 (20)	1.6 (52)	V	50
San Francisco, California	1969		1.4 (80)	1.6 (5)	1.2 (5)	1.5 (4)	1.0 (2)	1.3 (21)	0.9 (80)	V	229
	1970		0.9 (74)	1.7 (5)	0.9 (1)	1.1 (3)	0.9 (1)	1.1 (14)	0.9 (46)	V	50
Venezuela	1969								0.8 (22)	V	234
	1970								0.8 (23)	V	234
					Southern hemisphere						
Argentina	1969	1.3 (19)	1.4 (29)	1.2 (9)	1.3 (6)	—1.3— (9)		—1.3— (75)		V	45, 118
	1970	1.4 (9)	1.4 (21)	1.3 (12)	1.5 (10)	—1.4— (11)		—1.3— (69)		V	45, 118
Australia	1968	0.8 (79)	1.5 (98)	2.0 (26)	2.0 (14)	1.9 (8)	2.2 (14)	1.4 (75)	0.9 (75)	V	194
	1969	0.9 (108)	1.4 (98)	1.6 (27)	1.5 (11)	1.6 (7)	1.4 (13)	1.2 (136)	0.9 (112)	V	70
	1970	0.7 (208)	1.3 (86)	1.6 (23)	1.6 (12)	1.2 (9)	1.3 (7)	1.1 (90)	0.9 (130)	V	585
Brazil	1969								1.3 (45)	V	234, 417
Chile	1969								1.7 (20)	V	234
South Africa	1966–1969		1.1	———	———	1.3	———	2.0	0.5	Rib	623

[a] V represents vertebræ.

[b] The data up to 4 years refer to Moscow City only.

TABLE 35. ^{90}Sr IN ADULT VERTEBRÆ OF THE NORTHERN HEMISPHERE (pCi $(gCa)^{-1}$)

Year	Canada	Czechoslovakia	Denmark	France	Poland	USSR (Moscow)	United Kingdom	United States (New York)	Average
1962	1.2		0.8		1.4			1.0	1.10
1963	1.7		1.2		1.6	1.7		1.6	1.56
1964	3.1	1.8	2.4		2.5	2.4		2.0	2.37
1965	3.1	2.2	2.7	2.2	2.5	3.1	1.9	2.1	2.47
1966	2.6	1.8	2.6	2.1	2.9	2.7	2.2	2.1	2.37
1967	2.5	1.9	2.1	2.2		2.3	1.6	1.9	2.07
1968	2.7	1.7	1.9	2.3		1.7	1.6	1.9	1.97
1969	2.2	1.8	1.3	2.0		1.7		1.7	1.78
1970		1.7	1.3	1.9		1.4		1.6	1.58
1971			1.8			1.2			

TABLE 36. PARAMETERS OBTAINED BY FITTING THE ^{90}Sr BONE DATA (ADULT VERTEBRÆ) TO THAT IN DIET[a]

	New York, 1954-1970	San Francisco, 1961-1970	Denmark, 1960-1970	Northern hemisphere, 1954-1970	United Kingdom,[b] 1961-1969
c	0.027	0.011	0.001	0.023	
g	0.014	0.027	0.043	0.031	0.035
μ (y^{-1})	0.17	0.20	0.48	0.25	0.275
P_{34}	0.116	0.16	0.114	0.117	0.124

[a] The New York, San Francisco and Danish data were fitted using as the transfer function equation 30.

[b] In the fit to the United Kingdom data (478) the parameters were determined by simultaneously fitting an exponential transfer function (equation 28) to the ^{90}Sr in vertebræ and a double exponential transfer function (equation 29) to the ^{90}Sr in femur.

TABLE 37. DOSE COMMITMENTS FROM ^{90}Sr FROM ALL TESTS UP TO 1970 (mrad)

	Northern hemisphere		Southern hemisphere	
	Temperate latitudes	Average	Temperate latitudes	Average
Bone marrow	62	45	17	11
Endosteal cells	85	61	23	15

TABLE 38. RANGE AND ADOPTED VALUES OF THE PARAMETERS USED TO CALCULATE THE DOSE TO THE THYROID OF INFANTS FROM INGESTION OF MILK CONTAMINATED BY ^{131}I FALL-OUT

	Adopted value	Range
Deposition velocity (m s^{-1})	$5\ 10^{-3}$	$(1\text{-}20)\ 10^{-3}$
Transfer coefficient from deposition to milk (pCi d l^{-1} per pCi m^{-2})	0.8	0.23-1.5
Daily intake of fresh animal milk (litre)	0.7	0-1
Dose factor (μrad per pCi)	16.5	15.5-18.5

TABLE 39. ^{131}I IN MILK AND THYROID DOSES RESULTING FROM 1970 AND 1971 ATMOSPHERIC TESTS

Region, area or country	*Year*	*Integrated milk concentration (pCi d l^{-1})*	*Integrated thyroid doses to infants (mrad)*	*Reference*
Argentina				
Buenos Aires	1970	4,600	53	47
Australia				
Malanda	1970	5,800	67	67
	1971	5,300	61	68
Hobart-Launceston	1970	900	10	67
	1971	350	4	68
Country average	1970	1,500	17	67
	1971	1,100	13	68
Bolivia				
La Paz	1970	11,000	130	527
	1971	2,400	28	528
Brazil				
Guanabara	1970	3,600	42	622
Chile				
Santiago	1970	3,000	35	527
	1971	5,200	60	528
Colombia				
Bogotá	1970	900	10	527
Fiji				
Suva	1970	3,200	37	448, 449
	1971	2,400	28	451, 452
Malagasy Republic				
Diego Suarez	1971	6,400	74	528
New Caledonia				
Noumea	1970	3,000	35	527
	1971	2,600	30	528
New Zealand	1970	700	8	448, 449
	1971	300	3	451, 452
Peru				
Arequipa	1970	7,500	87	527
	1971	2,900	33	528
Society Islands				
Tahiti	1970	11,000	130	527
	1971	18,000	210	528
South Africa				
Cape Town	1970	1,500	17	624
Pretoria	1970	8,000	92	
Western Samoa				
Apia	1970	6,400	74	448, 449
	1971	7,100	82	451, 452

TABLE 40. ^{137}Cs BODY BURDENS (pCi (gK)$^{-1}$)

Region or country	Latitude	Sex	1964	1965	1966	1967	1968	1969	1970	1971	Reference
Northern hemisphere											
Belgium	~ 50°	MF	158	135	87	50	29				616
Canada (Ottawa)	~ 45°	MF		170							431
Denmark	55°-60°	MF	185	168	106	65	46	40	23	14	4, 5, 616
Egypt	~ 30°	MF				23	14		12		157, 438
Federal Republic of Germany	47°-55°										
Berlin		MF				68	48	47	36		
Karlsruhe		MF	151	111	81	49	27	16	15		92
Düsseldorf		M	243	186	128	76	41	32	31		
Finland	~ 60°	MF		182	150	107	72	53	44		590, 592
France	~ 50°	MF	227	194	93	64	36	32	26	28	490
Israel	~ 35°	M					48				170
Japan	30°-45°	M	93	77	54	33	20	14	13		444
Norway	~ 60°	MF		430	290						259
Poland	50°-55°	MF	164	185		71					311, 366
Sweden (Stockholm)	~ 60°	MF	205	187	139	107	74	54	47		388, 595
Switzerland (Geneva)	~ 45°	M	206	179	103	54	30	24	21		254
		F	139	121	66	41	26	19	18		
Union of Soviet Socialist Republics											
Moscow	~ 55°	M	258			50	34	29	38		665, 672, 685
		F				42	27	22	36		
Leningrad	~ 60°	MF	174	142	92	68	70				663, 684
United Kingdom	50°-60°	M		148	89	45					201
London area		F	149	109	60	33					
West Cumberland		M	257	190	110	52	30				242
United States average	25°-50°	MF	141	109	60	35	17				214
Florida	25°-30°	MF		149	132	120					533
Subarctic region											
Canada	60°-70°										
Eastern Arctic Eskimos		M			5,800						56
Central Arctic Eskimos		M				11,000					
Finland: Inari reindeer herders	65°-70°	M	7,800	9,000	7,800	5,500	5,200	3,400	3,100		519, 520, 521
		F	8,800	11,200	7,900	3,800	4,200	3,600	2,800		
Union of Soviet Socialist Republics											
Murmansk	65°-70°	M	14,000	18,000	21,500		16,500				679
United States, Alaska	65°-70°	M	9,100	6,600	4,900	4,300	2,400				108, 151, 524
Southern hemisphere											
Argentina	35°-40°				31	20	16	13	15		118
Australia	30°-40°			65	42	37	18		16		585, 616

TABLE 41. MEAN ANNUAL DOSES TO VARIOUS TISSUES (rad) RESULTING FROM THE INHALATION OF 1 μCi OF PuO_2 (628)

Time post-exposure (years)	Pulmonary region	Lymph nodes	Liver	Bone
a — 0.05 μm AMAD (pulmonary deposition fraction: 0.59)				
0-1	46	184	0.2	0.04
1-5	15	510	0.8	0.14
5-50	0.2	530	1.0	0.20
b — 0.10 μm AMAD (pulmonary deposition fraction: 0.50)				
0-1	39	156	0.2	0.04
1-5	13	430	0.7	0.12
5-50	0.2	450	0.9	0.17
c — 0.50 μm AMAD (pulmonary deposition fraction: 0.30)				
0-1	23	94	0.2	0.03
1-5	8	260	0.5	0.08
5-50	0.1	270	0.6	0.11

TABLE 42. ^{239}Pu CONTENT IN VARIOUS HUMAN ORGANS AND TISSUES (pCi kg^{-1})

Location	Year	Number of samples	Respiratory lymph nodes	Lung	Liver	Bone	Reference
United States							
New Jersey	1959		5.0	0.78			342
Union of Soviet Socialist Republics	1965	12	6.85				
	1965	14		0.15			686
	1966	12	9.6				
	1966	20		0.11			
United States							
Massachusetts	1965–1966	12		0.45	0.78		392
	1965–1966					0.05	
Los Alamos	1960–1971	60		0.5	0.7		439
Los Alamos[a]	1958	1	56 250	2 160	4 455	945	
	1959–1962	1	11 430	2 835	1 215	225	355
	1959–1962	1	200	27	9	0.45	
Rocky Flats[a]	1967	1	630	95	145	58	347

[a] Radiation employees.

TABLE 43. CONVERSION FACTORS FOR THE AIR-DOSE AT ONE METRE ABOVE A PLANE SOURCE (38)

	^{54}Mn	^{95}Zr	^{103}Ru	^{106}Ru	^{125}Sb	^{137}Cs[a]	^{140}Ba	^{141}Ce	^{144}Ce
Dose-rate conversion factor, mrad y^{-1} per mCi km^{-2}	0.119	0.341[b]	0.072	0.042	0.063	0.033	0.316[b]	0.011	0.004
Mean life, years	1.24	0.257	0.157	1.44	3.90	43.7	0.051	0.129	1.13
Dose-commitment conversion factor, mrad per mCi km^{-2}	0.147	0.087	0.011	0.060	0.246	1.44	0.016	0.0014	0.0045

[a] For ^{137}Cs the source is exponentially distributed with a mean depth of 3 cm.
[b] These factors include contributions from the daughter radio-nuclides assumed in transient equilibrium.

TABLE 44. EXTERNAL DOSE COMMITMENT FROM FALL-OUT (mrad)

	Northern hemisphere		Southern hemisphere	
	Temperate latitudes	Average	Temperate latitudes	Average
Short-lived radio-nuclides	65	47	19	13
Caesium-137	59	43	16	10

TABLE 45. DOSE COMMITMENTS FROM NUCLEAR TESTS CARRIED OUT BEFORE 1971. (THE DOSE COMMITMENTS FROM NUCLEAR TESTS CARRIED OUT BEFORE 1968, TAKEN FROM THE 1969 REPORT, ARE INDICATED BETWEEN PARENTHESES)

Source of radiation	Dose commitments (mrad) for the north temperate zone			Dose commitments (mrad) for the south temperate zone			Dose commitments (mrad) to the world population		
	Gonads	Bone-lining cells	Bone marrow	Gonads	Bone-lining cells	Bone marrow	Gonads	Bone-lining cells	Bone marrow
External									
Short-lived	65 (36)	65 (36)	65 (36)	19 (8)	19 (8)	19 (8)	44	44	44
^{137}Cs	59 (36)	59 (36)	59 (36)	16 (8)	16 (8)	16 (8)	40	40	40
^{85}Kr	2 10^{-4}	2 10^{-4}	2 10^{-4}	2 10^{-4}	2 10^{-4}	2 10^{-4}	2 10^{-4}	2 10^{-4}	2 10^{-4}
Internal									
^{3}H	4	4	4	1	1	1	4	4	4
^{14}C[a]	12 (13)	15 (16)	12 (13)	12 (13)	15 (16)	12 (13)	12	15	12
^{55}Fe	1	1	0.6	0.3	0.3	0.2	0.7	0.7	0.4
^{90}Sr		85 (130)	62 (64)		23 (28)	17 (14)		57	42
^{137}Cs	26 (21)	26 (21)	26 (21)	7 (4)	7 (4)	7 (4)	18	18	18
^{239}Pu[b]		0.2			0.05			0.1	
TOTAL[c]	170 (110)	260 (240)	230 (170)	55 (33)	81 (64)	72 (47)	120	180	160

[a] Dose accumulated up to year 2000. The total dose commitment to the gonads and bone marrow is about 140 mrad; it is about 170 mrad to cells lining bone surfaces.
[b] The dose commitment to bone-lining cells for the north temperate zone has been taken to be equal to the integrated dose over 50 years to bone. A reduction by a factor of four has been assumed for the south temperate zone. Because of insufficient data, the dose commitments to gonads and to bone marrow have not been estimated.
[c] Totals have been rounded off to two significant figures.

TABLE 46. REACTION PRODUCTS FOR AN UNDERGROUND EXPLOSION, CONSISTING OF ONE-MEGATON FUSION AND TEN-KILOTON FISSION (583)

Source	*Fission products (curies)*	*Induced products (curies)*[a]	*Fusion products (curies)*
Fission (10 kt) ..	$3.0\ 10^{9}$[b]	10^{5}	
^{90}Sr	$1.5\ 10^{3}$		
^{137}Cs	$1.6\ 10^{3}$		
^{60}Co		Small	
^{14}C		Small	
Fusion (1 Mt) ..		10^{8}	
^{3}H			$6.7\ 10^{6}$
^{60}Co		10^{4}	
^{14}C		15	

[a] Induced gamma-ray activities at one hour after detonation, based on average chemical composition of earth's crust.

[b] Fission-product gamma-ray activities at one hour after detonation, decaying at $t^{-1.2}$.

TABLE 47. SELECTED FISSION, FUSION, AND NEUTRON ACTIVATION PRODUCTS (AT DETONATION TIME) EXPECTED TO BE RELEASED TO THE ENVIRONMENT FOLLOWING A CRATERING EXPERIMENT WITH A 170-KT EXPLOSION (127)

		Amount released (kCi)		
			Remaining content	
Nuclide	*Half-life*	*Immediate fall-out*	*Main cloud*	*Base surge*
^{90}Sr	28 y	0.0011	0.0002	0.00005
^{103}Ru	40 d	1.0	0.16	0.014
^{106}Ru	370 d	0.08	0.013	0.0010
^{131}I	8 d	2.4	0.5	0.04
^{133}I	20 h	40	7	0.6
^{137}Cs	30 y	0.0015	0.0006	0.0002
^{3}H	12 y	500	1,000	500
^{32}P	14 d	1.2	0.24	0.02
^{48}Sc	44 h	16	1.4	0.09
^{181}W	140 d	30	5	0.6
^{185}W	75 d	60	10	1.1
^{187}W	24 h	800	140	14
^{203}Hg	47 d	3	0.5	0.06
^{202}Tl	12 d	70	12	1.2
^{203}Pb	52 h	4,000	600	70

TABLE 48. COMPARISON OF PRE-PRODUCTION RADIO-ACTIVITY IN GASBUGGY AND RULISON GAS (176, 568, 569)

	Gasbuggy	*Rulison*
Date	10 December 1967	10 September 1969
Place	San Juan Basin in New Mexico	Piceance Basin in Colorado
Yield	29 kt	48 kt
Depth	1.3 km	2.6 km
Tritium		
Total in gaseous products (Ci)	2,100	1,300
Pre-production concentration in gas ($pCi\ cm^{-3}$)	710	180
Krypton-85		
Total (Ci)	350	1,100
Pre-production concentration in gas ($pCi\ cm^{-3}$)	120	150

TABLE 49. DATA ON NUCLEAR EXPLOSIONS FOR PEACEFUL USES (221, 321, 607)

Event	Country	Date	Yield (kilotons)	Comments
Cratering explosions				
Sedan	USA	1962	100	Explosion in alluvium. Formation of a crater 390 m in diameter and 100 m deep
Sulky	USA	1964	0.09	Explosion in basalt. Formation of a mound (retarc) 24 m in diameter and 8 m high
Palanquin	USA	1965	4	Explosion in rhyolite. Formation of a crater 73 m in diameter and 43 m deep
Cabriolet	USA	1968	2.5	Explosion in rhyolite. Formation of a crater 220 m in diameter and 73 m deep
Buggy I	USA	1968	5.5	Explosion in basalt. First nuclear row-charge experiment (five 1.1 kt charges spaced 45.7 m apart). Formation of a crater 260 m long, 76 m wide and 20 m deep
Schooner	USA	1968	35	Explosion in tuff. Formation of a crater 74 m in diameter and 21 m deep
T-1	USSR		0.2	Explosion in sandstone and argillite. Formation of a crater 74 m in diameter and 21 m deep
"1003"	USSR		1.1	Explosion in siltstone. Formation of a crater 124 m in diameter and 20 m deep
"1004"	USSR		> 100	Explosion in sandstone and siltstone. Formation of two water reservoirs, one inside explosion crater and one outside. The dimensions of the crater are 410 m in diameter and 100 m in depth
Contained explosions				
Gnome	USA	1961	3.1	Explosion in salt. Cavity radius: 25 m
Handcar	USA	1964	10	Explosion in dolomite. The chimney dimensions are 42 m in diameter and 71 m in height
Gasbuggy	USA	1967	29	Explosion in gas-bearing formation to stimulate a low producing gas field
Rulison	USA	1969	48	Explosion in gas-bearing formation to stimulate a low producing gas field
A	USSR		1.1	Investigation of the possibility of creating an underground storage space in a salt mass — volume of the empty space: around 10,000 m^3
B	USSR		25	Investigation of the possibility of creating an underground storage space in a salt mass — volume of the cavity: 140,000 m^3
C	USSR		12.6	Detonation of three charges in two stages. Stimulation of the production in an oil field
D	USSR			Stimulation of gas production
E	USSR		30	Elimination of a runaway gas well

TABLE 50. ESTIMATES IN MILLIRADS OF WHOLE-BODY DOSES[a] TO HYPOTHETICAL USERS IN LOS ANGELES BASIN OF GASBUGGY DILUTED GAS[b] AND OF GAS PRODUCED IN THE SAME CONDITIONS AS GASBUGGY WITH THE NEW EXPLOSIVE DESIGN (CALCULATED FROM DATA IN REFERENCES 33 AND 285)

	Gasbuggy			*New design*[c]	
Source of exposure	^{3}H	^{14}C	^{85}Kr	^{3}H	^{85}Kr
Domestic use[d]					
Nonvented heating and appliances[e]	0.09	$4\ 10^{-4}$	$2\ 10^{-4}$	$1\ 10^{-3}$	$1\ 10^{-4}$
All appliances vented except range	0.01	$5\ 10^{-5}$	$3\ 10^{-5}$	$2\ 10^{-4}$	$2\ 10^{-5}$
Weighted average[f]	0.02	$9\ 10^{-5}$	$5\ 10^{-5}$	$3\ 10^{-4}$	$3\ 10^{-5}$
Atmosphere					
At point of peak concentration	0.01	$6\ 10^{-5}$	$3\ 10^{-5}$	$2\ 10^{-4}$	$2\ 10^{-5}$
Population weighted average	$2\ 10^{-3}$	$8\ 10^{-6}$	$4\ 10^{-6}$	$3\ 10^{-5}$	$3\ 10^{-6}$
Total					
Maximum exposure	0.1	$5\ 10^{-4}$	$2\ 10^{-4}$	$1\ 10^{-3}$	$1\ 10^{-4}$
Weighted average	0.02	$1\ 10^{-4}$	$5\ 10^{-5}$	$3\ 10^{-4}$	$3\ 10^{-5}$

[a] The whole-body dose factors are taken as 1, 2.8 and $1.4\ 10^{-2}$ μrad per pCi y m^{-3} for ^{3}H, ^{14}C and ^{85}Kr, respectively.

[b] The Gasbuggy gas production rate being assumed to be $28\ 10^{3}$ m^{3} d^{-1} and the natural gas consumption rate in the Los Angeles basin being $50\ 10^{6}$ m^{3} d^{-1}, the dilution factor is about 1,800.

[c] The production rate of ^{3}H per kiloton of yield is assumed to be 70 times less than for the device used for Gasbuggy (358). The concentration of ^{85}Kr is about six times more than that of ^{3}H and the dose from ^{14}C is negligible compared to that from ^{3}H and ^{85}Kr (647).

[d] Assumes an occupancy factor of 0.7, a 90 m^{2} residence of normal construction and an air infiltration rate of 220 m^{3} h^{-1}.

[e] Assumes 900° C-days of heating per year.

[f] Assumes nonvented heating for 10 per cent of the houses.

TABLE 51. ^{131}I CONTAMINATION OF MILK RESULTING FROM UNITED STATES NUCLEAR CRATERING EXPERIMENTS

Cratering event	*Location receiving significant concentrations of ^{131}I in milk*	*Integrated concentration*[a] *(pCi d l^{-1})*	*Thyroid dose to infants (mrad)*	*Population thyroid dose to infants (man-rads)*	*Reference*
Sedan (July 6, 1962)[b]	Salt Lake City, Utah	20,000	230	860	383
	Laramie, Wyoming	8,900	100	140	
Sulky (December 18, 1964)*					
Palanquin (April 14, 1965)	Helena, Montana	800	9	160	384
	Martin Ranch, Eureka, Nevada[c]	11,000	130	20	
Cabriolet (January 26, 1968)	Mountain View Ranch, Deeth, Nevada[c]	6,300	70	10	
Buggy I (March 12, 1968)	Pohlsander Ranch, Wells, Nevada[c]	5,500	60	10	
Schooner (December 8, 1968)	Boyd Schena Ranch, Abraham, Utah[c]	1,000	11	2	

* Not detected.

[a] The integrated concentration has been taken to be equal to 10 times the peak level concentration expressed in pCi l^{-1} (86).

[b] Five events may have contributed to the milk contamination attributed in this table to Sedan. When calculating the population dose, Sedan was assumed to account for only 16 per cent (average value of the range 2-30 per cent given by Mays (407) for Utah) of the milk contamination of Utah and Wyoming.

[c] Since the milk was taken from the ranch for the radiological monitoring, it was not available for consumption by members of the public and the corresponding dose given above is hypothetical.

TABLE 52. ACTIVITY OF SELECTED LONG-LIVED ISOTOPES (T>8 d) IN THE CLOUD FROM THE SCHOONER EXPERIMENT AND ESTIMATED DOSE COMMITMENTS TO THE POPULATION OF THE 40-50°N LATITUDE BAND[a]

Source of irradiation	*Activity (Ci)*	*Tissue at risk*	*Transfer coefficient (mrad per mCi km^{-2})*	*Dose commitment from the long-range fall-out (μrad)*	*Population dose commitment (man-rads)*
External irradiation					
Fission products:					
^{88}Y	110	Whole body	4.6 10^{-2}	1.6 10^{-1}	99
^{103}Ru	540		3.5 10^{-3}	6.0 10^{-2}	37
^{137}Cs	2.4		4.6 10^{-1}	3.5 10^{-2}	22
^{140}Ba	910		5.1 10^{-3}	1.5 10^{-1}	93
^{141}Ce	160		4.5 10^{-4}	2.3 10^{-3}	1.4
^{147}Nd	130		2.3 10^{-4}	9.5 10^{-4}	0.6
Activation products:					
^{54}Mn	190		4.7 10^{-2}	2.8 10^{-1}	170
^{57}Co	90		5.8 10^{-3}	1.7 10^{-2}	11
^{58}Co	540		1.2 10^{-2}	2.1 10^{-1}	130
^{74}As	770		2.5 10^{-3}	6.1 10^{-2}	38
^{181}W	180,000		1.3 10^{-5}	7.4 10^{-2}	46
Internal irradiation					
^{3}H	410,000	Whole body		8.6 10^{-1}	3,000
^{90}Sr	1.5	Bone marrow	7.7 10^{-1}	3.7 10^{-2}	23
		Endosteal cells	1.1	5.2 10^{-2}	32
^{137}Cs	2.4	Whole body	2.0 10^{-1}	1.5 10^{-2}	9

[a] Except for ^{3}H and ^{90}Sr, the activities were taken from reference 332. The ^{90}Sr activity was calculated assuming the ^{137}Cs/^{90}Sr ratio to be 1.6. Tritium activity was derived from the data given in table 47. The dose commitments were calculated by the Committee. Those from ^{3}H refer to the world population.

TABLE 53. ESTIMATED NUCLEAR ELECTRIC GENERATING CAPACITY FOR THE WORLD (GW(e))[a]

1980	*1990*	*2000*	*Reference*
216	684	1,596	419
75	390	1,200	114
250	800	2,000	476
120	430	1.030	284
350	1,600	4,300	581

[a] In 1970 the nuclear generating capacity was 20 GW(e) (264).

TABLE 54. DATA ON SELECTED FISSION PRODUCTS FROM ^{235}U FISSION IN THERMAL REACTORS (128, 567) AND FROM ^{239}Pu IN FAST REACTORS (174, 505)

Fission product	*Radio-active half-life*	*Fission yield (per cent)*		*Activity present in thermal reactors[a] operating at 20 MW(th)t^{-1} after 1,000 days of irradiation (Ci t^{-1})*
		^{239}Pu (fission spectrum neutrons)	*^{235}U (thermal neutrons)*	
^{3}H	12.3 y	0.025	0.013	3.1 10^{2}
^{85}Kr	10.7 y	0.15	0.28	7.6 10^{3}
^{89}Sr	50.4 d	1.7	4.8	8.0 10^{5}
^{90}Sr	28 y	2.1	5.6	6.1 10^{4}
^{95}Zr	65.5 d	4.3	6.2	1.0 10^{6}
^{103}Ru	39.6 d	6.4	2.9	4.8 10^{5}
^{106}Ru	369 d	4.6	0.38	5.4 10^{4}
^{129}I	1.7 10^{7} y	3.0	0.9	1.7 10^{-2}
^{131}I	8 d	4.6	3.1	5.2 10^{5}
^{131m}Xe	12 d	0.027	0.018	3.0 10^{3}
^{133}Xe	5.3 d	5.7	6.6	1.1 10^{6}
^{137}Cs	30 y	6.8	6.2	6.4 10^{4}
^{144}Ce	284 d	3.2	5.6	8.6 10^{5}

[a] The values have been calculated on the basis of fission of ^{235}U only. In practice, a substantial fraction of the fission occurring after some time in a thermal reactor arises from fissions of ^{239}Pu resulting from activation of ^{238}U (paragraph 340). The activities of some nuclides (e.g. ^{106}Ru) are therefore significantly different from the values given in the table.

TABLE 55. PRODUCTION OF ^{3}H, ^{85}Kr, AND ^{129}I FROM WORLD NUCLEAR POWER REACTORS[a]

		^{3}H	^{85}Kr	^{129}I
Production rate (Ci (MW(e) y)$^{-1}$):	thermal fission of ^{235}U ..	21	510	$1.0\ 10^{-3}$
	fast fission of ^{239}Pu	40	270	$3.4\ 10^{-3}$
Annual production (MCi):	1970	0.20	4.9	$9.7\ 10^{-6}$
	2000	74	740	$5.8\ 10^{-3}$
Integrated amount (MCi):	1970	0.97	24	$4.6\ 10^{-5}$
	2000	550	$8.1\ 10^{3}$	$3.8\ 10^{-2}$
Cumulative amount (MCi):	1970	0.81	19	$4.6\ 10^{-5}$
	2000	420	$5.5\ 10^{3}$	$3.8\ 10^{-2}$

[a] The power produced in 1970 was 9.7 GW(e) (paragraph 314). It is assumed that the growth of the nuclear power industry will follow the highest estimate in table 53 (581) and that 40 per cent of the nuclear power produced in 1990, and 70 per cent of that produced in 2000, will be from fast reactors (465). A load factor of 0.5 and a thermal efficiency of 0.3 are assumed (paragraph 338).

TABLE 56. DATA ON SELECTED ACTIVATION PRODUCTS INDUCED BY THERMAL NEUTRONS (516)

Radio-active product	*Half-life*	*Target nuclide*	*Isotopic abundance (per cent)*	*Activation cross-section (barns)*
^{3}H	12.3 y	^{2}H	0.015	0.0005
^{3}H	12.3 y	^{6}Li	7.42	950
^{3}H	12.3 y	^{10}B	19.7	3,800
^{14}C	5,730 y	^{13}C	1.1	0.0009
^{16}N	7.4 s	^{16}O[a]	99.8	0.00018
^{24}Na	14.9 h	^{23}Na	100	0.53
^{41}Ar	1.8 h	^{40}Ar	99.6	0.61
^{51}Cr	28 d	^{50}Cr	4.3	17
^{56}Mn	2.6 h	^{55}Mn	100	13
^{58}Co	72 d	^{58}Ni	67.8	0.04-0.2[b]
^{60}Co	5.3 y	^{59}Co	100	37
^{64}Cu	12.8 h	^{63}Cu	69	4.5
^{65}Zn	250 d	^{64}Zn	48.9	0.46
^{95}Zr	65.5 d	^{94}Zr	17.4	0.08
^{134}Cs	2.0 y	^{133}Cs	100	31
^{239}Pu	24,400 y	^{238}U	99.3	2.7

[a] ^{16}O gives also rise to ^{13}N according to the reaction ^{16}O (p, α)^{13}N.
[b] Range of values reported for fission spectrum neutrons (531).

TABLE 57. TRITIUM IN LIQUID WASTE DISCHARGED FROM WATER-COOLED REACTORS

Reactor	*Power MW(e)*	*Annual quantity discharged (Ci)*			*Annual quantity discharged per unit of power generated[a] (Ci (MW(e) y)$^{-1}$)*			*Reference*
		1968	*1969*	*1970*	*1968*	*1969*	*1970*	
BWR								
Dresden-I, USA	200	3	6	5	0.03	0.06	0.03	155, 306, 372
Oyster Creek, USA	515		5	22		0.12	0.05	345
Nine Mile Point, USA	500			20			0.09	345
Garigliano, Italy	150	8	7	5	0.07	0.05	0.06	117
KRB Gundremmingen, Federal Republic of Germany	250	21	18		0.19	0.13		24
PWR								
Yankee Rowe, USA[b]	175	1,200	1,200	1,500	8.3	8.7	10.3	155, 306, 372
Indian Point I, USA[b]	265	790	1,100	410	4.3	5.3	9.4	155, 306, 372
San Onofre, USA[b]	430	2,300	3,500	4,800	14.9	11.1	13.1	155, 306, 372
Conn. Yankee, USA[b]	575	1,700	5,200	7,400	4.7	11.9	17.4	155, 306, 372
Ginna, USA	420			110			0.4	306
Trino Vercellese, Italy	250			135			1.0	117
Ardennes, France/Belgium.. ..	240			340			2.4	158
PHWR								
Douglas Point, Canada	210	440	1,000	950		20.4	8.9	400

[a] Power generation data taken from references 143 and 263.
[b] Stainless steel cladding used on fuel elements in these reactors allows greater diffusion of fission product ^{3}H into the coolant than the zircaloy cladding used on fuel elements in Dresden-I (BWR) and Ginna (PWR) in the United States.

TABLE 58. TRITIUM IN LIQUID WASTE DISCHARGED FROM GAS-COOLED REACTORS

Reactor	Power MW(e)	Annual quantity discharged (Ci) 1969	Annual quantity discharged (Ci) 1970	Annual quantity discharged per unit of power generated[a] (Ci (MW(e) y)$^{-1}$) 1969	Annual quantity discharged per unit of power generated[a] (Ci (MW(e) y)$^{-1}$) 1970	Reference
Berkeley, UK	280	61	61	0.21	0.21	146, 499
Bradwell, UK	300	180	95	0.63	0.46	146, 499
Hinkley Point, UK	500	35	19	0.08	0.08	146, 499
Trawsfynydd, UK	500	230	68	0.60	0.18	146, 499
Dungeness, UK	550	72	19	0.17	0.05	146, 499
Sizewell, UK	580	10	21	0.03	0.05	146, 499
Oldbury, UK	600	16	68	0.05	0.23	146, 499
Hunterston, UK	320	250		0.81		89
Latina, Italy	200	25	17	0.34	0.13	117

[a] Power generation data taken from reference 263.

TABLE 59. ANNUAL QUANTITY (IN CURIES) OF RADIO-NUCLIDES IN LIQUID WASTE DISCHARGED FROM WATER-COOLED REACTORS

Radio-nuclide	Dresden-I, USA (BWR-200 MW(e)) (305), 1968[b]	Humboldt Bay, USA (BWR-68 MW(e)) (374), 1970	Indian Point I, USA[a] (PWR-265 MW(e)), 1969	KRB Gundremmingen, Federal Republic of Germany (BWR-250 MW(e)) (24) 1968	KRB Gundremmingen, Federal Republic of Germany (BWR-250 MW(e)) (24) 1969	Douglas Point, Canada (PHWR-210 MW(e)) (31) 1970
^{54}Mn	0.006	0.24	5			0.06
^{55}Fe	0.08					
^{58}Co	0.8		5	0.2	0.2	0.04
^{60}Co	1.1	0.84	4	0.1	0.09	4
^{65}Zn		0.12				0.04
^{89}Sr	0.3	0.01	0.03	0.7	1.6	<0.0002
^{90}Sr	0.03	0.01	0.002	0.02	0.09	<0.01
^{91}Y	0.03					
^{131}I	0.04	0.09	3	0.5	0.7	0.9
^{134}Cs	0.07	0.24	4			4
^{137}Cs	0.2	0.84	6	0.7	0.2	12
^{140}Ba	0.2			0.2	0.2	
^{144}Ce	0.06					
TOTAL	2.9	2.4	27	2.4	3.0	21

[a] Calculated from data in reference 357.
[b] Calculated from five trips during a 9-month period of study.

TABLE 60. ANNUAL QUANTITY (CURIES) OF RADIO-NUCLIDES[a] IN LIQUID WASTE DISCHARGED FROM GAS-COOLED REACTORS IN THE UNITED KINGDOM, IN 1969 (89)

Radio-nuclide	Berkeley (280 MW(e))	Bradwell (300 MW(e))	Hinkley Point (500 MW(e))	Trawsfynydd (500 MW(e))	Dungeness (550 MW(e))
^{32}P		0.33			
^{35}S	7.3	14	12	1.3	21
^{45}Ca				0.77	
^{55}Fe					2.8
^{60}Co		0.56			
^{65}Zn		0.086[b]			
^{89}Sr	2.4				
^{90}Sr + ^{90}Y	4.2		13	1.9	4.9
^{110}Ag					0.46
^{134}Cs	9.7	22	35	0.039	20
^{137}Cs	32	65	130	0.43	56
^{144}Ce + ^{144}Pr	6.4				

[a] The radio-nuclides for which figures are given for a station are those which are most important radiologically and/or numerically at that station.
[b] Result taken from station's monthly returns of radio-activity discharged.

TABLE 61. NOBLE GASES DISCHARGED FROM POWER REACTORS

Reactor site	Type	Net output (MW(e))	Criticality date	Annual quantity discharged (curies) 1967	1968	1969	1970	Comments	Reference
Dresden-I, USA	BWR	200	1959	260,000	240,000	800,000	914,000	Fission gases whose detailed composition is given in table 63. Use of 23-min hold-up line	121
Big Rock, USA		70	1962	264,000	232,000	200,000	277,000	30-min hold-up line	305
Humboldt Bay, USA		68	1963	900,000	897,000	490,000	535,000	18-min hold-up line	374
La Crosse, USA		50	1967	< 5	< 1	480	700	20-min hold-up line	535
Oyster Creek, USA		515	1969			7,000	112,000	30-min hold-up line	
Nine Mile Point, USA		500	1969			55	9,500	30-min hold-up line	
Garigliano, Italy		150	1963	29,200	82,000	140,000	275,000		117
VAK, Federal Republic of Germany		15	1960	3,900	4,600	1,800	3,400	Mainly ^{133}Xe. Storage tanks	63
KRB, Federal Republic of Germany		250	1966			9,000		Mainly ^{133}Xe. 40-min hold-up line + charcoal beds	
KWL, Federal Republic of Germany		240	1968			200,000	130,000	Mainly ^{133}Xe. 60-min hold-up line + charcoal beds	
Tsuruga, Japan		330	1969				68,000	30-min hold-up line + 24-h decay tanks	608
Yankee Rowe, USA	PWR[a]	175	1960	2.3	0.7	4	17.2		121
Saxton, USA		3	1962	22	18.6	1			305
Indian Point-I, USA		265	1962	23	60	600	1,750		374
San Onofre, USA		430	1967	4	4.8	260	1,610		535
Connecticut Yankee, USA		575	1967	0.02	3.7	190	700	^{133}Xe(86%), ^{135}Xe(12%), ^{85}Kr(1.4%), ^{41}Ar(0.4%)	
Ginna, USA		420	1969				9,980		
Trino Vercellese, Italy		250	1964	59.1			19.2		117
Ardennes, France		240	1966	2.1			3		158
KWO, Federal Republic of Germany		300	1968			5,500	7,700	Mainly ^{133}Xe	63
Mihama, Japan		340	1970				1,200		608
Bradwell, UK	GCR	300	1962				7,600	^{41}Ar only. Annual quantity discharged calculated using a load factor of 0.8	499
Hinkley, UK		500	1964				86,000		
Trawsfynydd, UK		500	1964				56,000		
Chinon, France		750	1966	23,000	16,400	12,300	8,100	Mainly ^{41}Ar produced by activation of the coolant	158
Saint-Laurent, France		490	1969			1,900	300		
Latina, Italy		200	1962	2,500	2,500	1,500	2,500		117
Tokai, Japan		160	1966	3,400	3,000	3,400	6,300	^{41}Ar is the major constituent	608
NPD, Canada	PHWR	22	1962			16,000		Noble gases only. ^{41}Ar in the proportion of 50 per cent or less	400
Douglas Point, Canada		210	1966		40,000	100,000	160,000		

[a] All PWRs are equipped with storage tanks allowing for a delay before discharge of up to 120 days.

TABLE 62. REACTOR OFF-GAS COMPOSITION AT VARIOUS DECAY TIMES (PER CENT) (61)

Isotope	*Half-life*	*30 minutes*	*1 hour*	*8 hours*	*1 day*	*3 days*	*10 days*	*30 days*	*90 days*	*150 days*
^{89}Kr	3.2 min	0.3								
^{137}Xe	3.8 min	0.9								
^{135m}Xe	15 min	8.0	3.0							
^{138}Xe	17 min	26.7	11.8							
^{87}Kr	1.3 h	15.7	18.0	1.4						
^{83m}Kr	1.9 h	2.5	3.1	0.8						
^{88}Kr	2.8 h	17.4	22.9	13.6	0.7					
^{85m}Kr	4.4 h	5.8	8.1	8.9	1.0					
^{135}Xe	9.2 h	17.6	25.2	50.0	38.5	2.3				
^{133m}Xe	2.3 d	0.2	0.3	0.9	1.8	2.1	0.5			
^{133}Xe	5.3 d	5.0	7.5	24.3	57.0	95.0	98.4	91.2	0.4	
^{131m}Xe	12.0 d			0.1	0.2	0.4	0.6	1.8	0.8	0.03
^{85}Kr	10.7 y				0.1	0.2	0.5	7.0	98.8	99.97

TABLE 63. AVERAGE DISCHARGE RATE OF RADIO-ACTIVE GASES FROM DRESDEN-I, IN THE UNITED STATES (305)

		Discharge rate (μCi s^{-1})		
Isotope	*Half-life*	*Measured*	*Computed for a 21-minute delay*	*Discharge/ generation*[a]
^{89}Kr	3.2 min		140	
^{137}Xe	3.8 min		320	
^{13}N	10 min		450	
^{135m}Xe	15 min		370	
^{138}Xe	17 min	3,000	2,800	$2\ 10^{-7}$
^{87}Kr	1.3 h	790	1,170	$6\ 10^{-7}$
^{83m}Kr	1.9 h		220	
^{88}Kr	2.8 h	740	1,250	$7\ 10^{-7}$
^{85m}Kr	4.4 h	400	370	$1\ 10^{-6}$
^{135}Xe	9.2 h	1,250	1,310	$2\ 10^{-6}$
^{133m}Xe	2.3 d	14	14	$6\ 10^{-6}$
^{133}Xe	5.3 d	510	380	$1\ 10^{-5}$
^{85}Kr	10.7 y	0.14	0.60	$5\ 10^{-5}$

[a] This column gives the quantity discharged as a fraction of the quantity generated in fuel.

TABLE 64. TRITIATED WATER AND GASEOUS IODINE DISCHARGED TO ATMOSPHERE FROM WATER-COOLED REACTORS

	Annual quantity discharged (curies)				
	Yankee Rowe, USA (PWR-175 MW(e)) (303), 1969-1970	*Dresden-I, USA (BWR-200 MW(e)) (304), 1968*	*Douglas Point, Canada (PHWR-210 MW(e)) (400)*		
Radio-nuclide			*1968*	*1969*	*1970*
^{3}H	13	$2\ 10^{-1}$	2,500	9,500	1,000
Gaseous ^{131}I	$< 3\ 10^{-4}$	$3\ 10^{-2}$	$7.3\ 10^{-2}$	$1.8\ 10^{-1}$	$2.2\ 10^{-1}$

TABLE 65. ESTIMATES OF DOSE DUE TO MEASURED CAESIUM CONCENTRATIONS IN FISH

Reactor	*Mean caesium concentration in fish (pCi g⁻¹ wet)*	*Source of activity*	*Annual whole-body dose to individuals concerned per unit rate of fish consumption (rad (g d⁻¹)⁻¹)*	*Individual dose commitment, per unit of fish consumption and unit rate of power generation[a] (rad kg⁻¹ (MW(e))⁻¹)*	*Reference*
Dresden-I, USA (1968) ..	0.015	Fall-out ^{137}Cs[b]			304
Indian Point I, USA (1969)	0.056	Total ^{137}Cs			
	0.022	Fall-out ^{137}Cs	$3\ 10^{-7}$		357
	0.026	Discharged ^{134}Cs	10^{-6}	$1.3\ 10^{-8}$	
	(calc.) 0.034	Discharged ^{137}Cs			
Trawsfynydd, UK (1969)[c] .	11	Total ^{137}Cs in trout	$2\ 10^{-4}$	$1.4\ 10^{-6}$	323, 426
	1.0	Discharged ^{134}Cs in trout			
	25	Total ^{137}Cs in perch			
	2.4	Discharged ^{134}Cs in perch			

[a] The rate of power generation in 1969 was taken from reference 263.
[b] Paragraph 356.
[c] Values for 1970 were somewhat lower than those for 1969 (427).

TABLE 66. POPULATION DOSE COMMITMENTS DUE TO DISCHARGES FROM SELECTED NUCLEAR POWER STATIONS IN THE UNITED KINGDOM CALCULATED FROM DATA IN REFERENCES 263 AND 323

Station and pathway	*Critical material*	*Exposed population group*	*Daily consumption rate or annual hours of exposure*	*Important radio-nuclides*	*Whole body dose-commitment to individuals concerned per unit of power generated (rad(MW(e) y)⁻¹)*	*Population dose commitment per unit of power generated (man-rad (MW(e) y)⁻¹)*
Bradwell						
Internal	Oyster	Oyster fishermen (50 persons)	75 g d⁻¹	^{65}Zn (critical) ^{137}Cs ^{110m}Ag ^{32}P	$1.1\ 10^{-6}$	$5.5\ 10^{-5}$
Trawsfynydd						
Internal	Trout and perch flesh	Lake anglers (100 persons)	100 g d⁻¹	^{137}Cs ^{134}Cs	$5.2\ 10^{-5}$	$5.2\ 10^{-3}$
Hinkley Point						
Internal	Fish and shrimp flesh	Local fishermen and families (100 persons)	90 g d⁻¹	^{137}Cs ^{134}Cs	$9.1\ 10^{-7}$	$9.1\ 10^{-5}$
External	Mud/silt	Local fishermen (10 persons)	880 h y⁻¹	^{137}Cs ^{134}Cs	$2.3\ 10^{-6}$	$2.3\ 10^{-5}$

TABLE 67. CALCULATED DOSES TO UNSHIELDED INDIVIDUALS AND POPULATIONS IN THE VICINITY OF UNITED STATES NUCLEAR POWER PLANTS BASED ON NOBLE GASES DISCHARGED IN 1969 (188)

Reactor site	Type	Annual doses for 1969: Dose at boundary (rad)	Within circle of 6.4 km radius: Population (units)	Within circle of 6.4 km radius: Population dose (man-rad)	Within circle of 6.4 km radius: Average dose (rad)	Within circle of 80 km radius: Population (thousands)	Within circle of 80 km radius: Population dose (man-rad)	Within circle of 80 km radius: Average dose (rad)	Years of production (to December 1970)	Power produced in 1969 (263) (MW(e) y)	Dose to individuals at boundary per unit of power (rad (MW(e) y)$^{-1}$)	Population dose within circle of 80 km radius per unit of power (man-rad (MW(e) y)$^{-1}$)
Dresden-I	BWR	$1.8\ 10^{-2}$	2,577	11	$4.3\ 10^{-3}$	5,715	360	$6.3\ 10^{-5}$	11	100	$1.8\ 10^{-4}$	3.6
Big Rock	BWR	$3.2\ 10^{-3}$	1,430	0.57	$4.0\ 10^{-4}$	100	3.64	$3.6\ 10^{-5}$	8	48	$6.7\ 10^{-5}$	$7.6\ 10^{-2}$
Humboldt Bay	BWR	$1.5\ 10^{-1}$	18,940	68.5	$3.6\ 10^{-3}$	101	107	$1.1\ 10^{-3}$	8	44	$3.4\ 10^{-3}$	2.4
La Crosse	BWR	$5\ 10^{-4}$	934	0.042	$4.5\ 10^{-5}$	328	0.301	$9.2\ 10^{-7}$	3	9	$5.6\ 10^{-5}$	$3.3\ 10^{-2}$
Nine Mile Point	BWR	$5\ 10^{-6}$	1,310	0.001	$7.6\ 10^{-7}$	533	0.012	$2.3\ 10^{-8}$	1	8	$6.2\ 10^{-7}$	$1.5\ 10^{-3}$
Oyster Creek	BWR	$3.7\ 10^{-4}$	3,619	0.082	$2.3\ 10^{-5}$	1,158	0.606	$5.2\ 10^{-7}$	1	40	$9.2\ 10^{-6}$	$1.5\ 10^{-2}$
Yankee Rowe	PWR	$1.1\ 10^{-4}$	1,180	0.0217	$1.8\ 10^{-5}$	1,209	0.70	$5.8\ 10^{-7}$	10	138	$8.0\ 10^{-7}$	$5.1\ 10^{-3}$
Indian Point I	PWR	$5.5\ 10^{-5}$	38,740	0.130	$3.4\ 10^{-6}$	13,324	1.94	$1.5\ 10^{-7}$	8	206	$2.7\ 10^{-7}$	$9.4\ 10^{-3}$
Conn. Yankee	PWR	$5\ 10^{-3}$	5,062	1.150	$2.3\ 10^{-4}$	2,682	15.56	$5.8\ 10^{-6}$	3	438	$1.1\ 10^{-5}$	$3.6\ 10^{-2}$
San Onofre	PWR	$2.3\ 10^{-4}$	5,470	0.047	$8.6\ 10^{-6}$	2,696	1.02	$3.8\ 10^{-7}$	3	314	$7.3\ 10^{-7}$	$3.2\ 10^{-3}$
Ginna	PWR	$5\ 10^{-6}$	5,001	0.0011	$2.2\ 10^{-7}$	953	0.0077	$8.1\ 10^{-9}$	1	17	$2.9\ 10^{-7}$	$4.5\ 10^{-4}$

TABLE 68. CALCULATED DOSES TO UNSHIELDED INDIVIDUALS AT THE BOUNDARY OF NUCLEAR POWER PLANTS DUE TO NOBLE GASES DISCHARGED

Reactor site	Type	Distance from stack taken as boundary	Dose at boundary (rad y^{-1})	Comments on the dose calculation	Years of production (up to December 1970)	Power produced in 1970 (263) (MW(e) y)	Dose to individuals at boundary per unit of power (rad (MW(e) y)$^{-1}$)
Garigliano, Italy	BWR	1,000 m	$6.7\ 10^{-3}$	Reported dose to a group of population living at 1 km from the stack for the year 1970 (117)	7	85	$7.9\ 10^{-5}$
KWL and KRB, Federal Republic of Germany	BWR	500 m	$4\ 10^{-4}$	Estimated dose due to typical noble gas emission from a German BWR power plant (24)	4	174	$2.3\ 10^{-6}$
KWO, Federal Republic of Germany	PWR	500 m	$9\ 10^{-5}$	Estimated dose due to typical noble gas emission from a German PWR power plant (24)	2	289	$3.1\ 10^{-7}$
Bradwell, UK	GCR		$6.1\ 10^{-4}$	Doses calculated from the ^{41}Ar releases given in table 61 assuming a dilution factor of $4\ 10^{6}$ m^3 s^{-1}	8	207	$2.9\ 10^{-6}$
Hinkley, UK	GCR		$6.9\ 10^{-3}$		6	238	$2.9\ 10^{-5}$
Trawsfynydd, UK	GCR		$4.5\ 10^{-3}$		6	388	$1.6\ 10^{-5}$
Oldbury, UK	GCR		Nil		3	291	Nil
Chinon, France	GCR		$6.5\ 10^{-4}$		5	411	$1.6\ 10^{-6}$
Saint-Laurent, France	GCR		$2.4\ 10^{-5}$	Doses calculated assuming that the releases given in table 61 consist of ^{41}Ar only and that the dilution factor is $4\ 10^{6}$ m^3 s^{-1}	2	89	$2.7\ 10^{-7}$
Latina, Italy	GCR		$2.0\ 10^{-4}$		8	136	$1.5\ 10^{-6}$
Tokai, Japan	GCR		$5.1\ 10^{-3}$		5	98	$5.2\ 10^{-5}$
NPD, Canada	PHWR	1,500 m	$8\ 10^{-4}$	The ratio of the dose to the discharge is assumed to be the same for Douglas Point and NPD	8	16	$5.0\ 10^{-5}$
Douglas Point, Canada	PHWR	1,500 m	$8\ 10^{-3}$	Reported dose (400)	4	107	$7.5\ 10^{-5}$

TABLE 69. RADIO-NUCLIDES IN LIQUID WASTES DISCHARGED FROM REPROCESSING PLANTS

Radio-nuclide	Quantity discharged (curies)				
	NFS, USA (393), May-October, 1969	Windscale, UK (654), 1969	Eurochemic, Belgium (625)		
			1967	1968	1969
^{3}H	1,700				
^{54}Mn	0.0027				
^{60}Co	0.20				
^{90}Sr	8.3	2,500	0.16	0.13	0.24
^{95}Zr	0.0046				
^{106}Ru	52	23,000			
^{125}Sb	0.59				
^{134}Cs	2.0				
^{137}Cs	8.0				
^{144}Ce	0.16	14,000			
^{147}Pm	0.092				

TABLE 70. TRITIUM IN LIQUID WASTE DISCHARGED FROM THE LAGOON SYSTEM OF THE NUCLEAR FUEL SERVICES REPROCESSING PLANT IN THE UNITED STATES (373)

Year	Quantity discharged (Ci)	Fuel processed (t)	Quantity discharged per tonne of fuel processed ($Ci\ t^{-1}$)
1966 (from second quarter)	290	110	3
1967	4,200	120	35
1968	2,600	140	19
1969	6,000	120	50
1970 (to third quarter)	3,600	35	103

TABLE 71. PARTICULATE AND GASEOUS RADIO-NUCLIDES DISCHARGED TO ATMOSPHERE FROM THE NUCLEAR FUEL SERVICES REPROCESSING PLANT

Radio-nuclide	Average discharge[a] ($Ci(MW(e)\ y)^{-1}$)
^{60}Co	$5\ 10^{-9}$
^{90}Sr	$3\ 10^{-8}$
^{106}Ru	$4\ 10^{-8}$
^{134}Cs	$2\ 10^{-8}$
^{137}Cs	$8\ 10^{-8}$
^{144}Ce	$1\ 10^{-7}$
^{238}Pu	$7\ 10^{-10}$
^{239}Pu	$1.5\ 10^{-9}$
^{3}H	$5\ 10^{-2}$
Gaseous ^{129}I[b]	$2\ 10^{-4}$
^{85}Kr	$5\ 10^{2}$

[a] Calculated from data in reference 115.
[b] The scrubbers were not in operation during the dissolution cycles.

TABLE 72. ESTIMATES OF DOSE DUE TO MEASURED ^{106}Ru AND ^{137}Cs CONCENTRATIONS IN AQUATIC FOOD-STUFFS

Reprocessing plant	Mean concentration ($pCi\ g^{-1}$ wet)	Nuclide and daily consumption rate of food-stuff	Annual dose to individuals concerned at stated consumption (rad)	Dose to individuals concerned per unit of power generated ($rad(MW(e)\ y)^{-1}$)	Reference
NFS					
1968	0.63	^{137}Cs in 15 g d^{-1} fish (including fall-out)	$2.1\ 10^{-4}$ to whole-body	$7.5\ 10^{-8}$	556
	0.85	^{106}Ru in 15 g d^{-1} fish	$9.1\ 10^{-4}$ to gastro-intestinal tract	$3.2\ 10^{-7}$	
Windscale					
1969	~ 15	^{106}Ru in 16 g d^{-1} laverbread	~ $1.7\ 10^{-2}$ to gastro-intestinal tract	$3.4\ 10^{-6}$[a]	426
1970	~ 7		~ $8.0\ 10^{-3}$ to gastro-intestinal tract	$1.6\ 10^{-6}$[b]	427

[a, b] Corresponding to population dose commitments of $8.8\ 10^{-2}$ and $4.2\ 10^{-2}$ man-rad $(MW(e)\ y)^{-1}$, respectively, to the gastro-intestinal tract, and $8.8\ 10^{-5}$ and $4.2\ 10^{-5}$ man-rad $(MW(e)\ y)^{-1}$ to the gonads (paragraph 389).

TABLE 73. POPULATION DOSE COMMITMENTS RESULTING FROM DISCHARGES FROM WINDSCALE TO THE IRISH SEA (UNITED KINGDOM) CALCULATED FROM DATA IN REFERENCES 323 AND 426

Exposure pathway	*Aquatic material*	*Exposed population group*	*Daily consumption rate or annual hours of exposure*	*Exposed organ*	*Radio-nuclides contributing to exposure*	*Dose commitment to individuals concerned per unit of power generated (rad (MW(e) y)$^{-1}$)*	*Population dose commitment per unit of power generated (man-rad^{-1} (MW(e) y)$^{-1}$)*
Internal	Porphyra (seaweed)	Laverbread consumers in South Wales, 2.6 × 10^4 persons	16 g laverbread	Gastro-intestinal tract	Mainly ^{106}Ru	$3.4\ 10^{-6}$ [a]	$8.8\ 10^{-2}$ [a]
				Gonads		$3.4\ 10^{-9}$	$8.8\ 10^{-5}$ [a]
External	Estuarine silt	Fishermen (10 persons)	350 h	Total body	^{95}Zr, ^{95}Nb, ^{106}Ru	$1.0\ 10^{-5}$	$1.0\ 10^{-4}$
Internal	Fish	Local fishermen (100 persons)	25 g fish	Gastro-intestinal tract	^{106}Ru	$4.0\ 10^{-7}$	$4.0\ 10^{-5}$
				Total body	^{137}Cs	$1.0\ 10^{-7}$	$1.0\ 10^{-5}$ [b]
External	Fishing gear	Fishermen (100 persons)	500 h	Hands	^{106}Ru, ^{144}Ce	$4.0\ 10^{-6}$	$4.0\ 10^{-4}$

[a] These values are estimated from measurements made in 1969; the comparable values for 1970 are about half of these (427).

[b] This value is estimated for the critical group of 100 persons; a value of $3.0\ 10^{-2}$ man-rad (MW(e) y)$^{-1}$ is applicable for 1970, if doses from consumption of plaice caught commercially in the Irish Sea are included in the estimation. It is doubtful whether fish in the Irish Sea in 1970 had reached equilibrium with radio-caesium in sea water and therefore, this dose commitment may be an underestimate (427).

TABLE 74. LOCAL AND GLOBAL DOSES RESULTING FROM ^{85}Kr AND ^{3}H DISCHARGED FROM THE NUCLEAR POWER INDUSTRY

	^{85}Kr	^{3}H
Local (airborne ^{85}Kr and ^{3}H)		
Gonad dose commitment to individuals concerned within a few kilometres of plant per unit power generated (rad (MW(e) y)$^{-1}$)	$2.7\ 10^{-8}$	$6.3\ 10^{-10}$
Gonad population dose to population within 250 km of plant per unit power generated (man-rad (MW(e) y)$^{-1}$)	$5.4\ 10^{-3}$	$1.3\ 10^{-4}$
Global (airborne ^{85}Kr and water-borne ^{3}H)		
Gonad dose commitment per unit power generated (rad (MW(e) y)$^{-1}$)	$3.1\ 10^{-11}$	$4.4\ 10^{-11}$

TABLE 75. SUMMARY OF ESTIMATED DOSE COMMITMENTS RESULTING FROM DISCHARGES OF RADIO-NUCLIDES BY THE NUCLEAR POWER INDUSTRY[a]

	Source of radiation	Relevant tissue	Number of individuals concerned	Dose commitment, average to individuals concerned per unit of power generated by thermal reactors (rad (MW(e) y)$^{-1}$)	Population dose commitment per unit of power generated by thermal reactors (man-rad (MW(e) y)$^{-1}$)	Dose commitment to the world population per year of generation of electricity: At the 1970 generation rate (rad) (GW(e) y)		Dose commitment to the world population per year of generation of electricity: at the estimated rate for the year 2000 of 2,150 GW(e) y[b] (rad)	Tables and paragraphs to be read in conjunction with these data
GLOBAL DOSES									
Fuel reprocessing plants	^{85}Kr	Gonads	$3.5\ 10^{9}$	$3.1\ 10^{-11}$	$1.1\ 10^{-1}$	$3.0\ 10^{-7}$	(9.7)	$4.5\ 10^{-5}$	Table 74, paragraph 396
	^{3}H	Whole body	$3.5\ 10^{9}$	$4.4\ 10^{-11}$	$1.5\ 10^{-1}$	$4.3\ 10^{-7}$	(9.7)	$1.6\ 10^{-4}$	Table 74, paragraph 397
LOCAL DOSES[c]									
EXTERNAL RADIATION									
Five USA reactors (built 1959-1963)	Short-lived noble gases	Whole body	$2.0\ 10^{7}$	$4.4\ 10^{-8}$	$8.8\ 10^{-1}$	$1.2\ 10^{-7}$	(0.46)		Table 67, paragraph 359
Six USA reactors (built 1967-1969)	Short-lived noble gases	Whole body	$8.4\ 10^{6}$	$2.5\ 10^{-9}$	$2.1\ 10^{-2}$	$1.0\ 10^{-8}$	(1.7)		Table 67, paragraph 359
Fuel reprocessing plants ..	^{85}Kr	Gonads	$2.0\ 10^{7}$	$2.7\ 10^{-10}$	$5.4\ 10^{-3}$	$1.5\ 10^{-8}$	(9.7)	$2.2\ 10^{-6}$	Table 74, paragraph 392
Doses calculated from recorded concentrations around a particular installation									
Reactor: Hinkley Point, UK	$^{134}Cs + ^{137}Cs$	Whole body	10	$2.3\ 10^{-6}$	$2.3\ 10^{-5}$	$1.6\ 10^{-12}$	(0.24)		Table 66, paragraph 358
Fuel reprocessing plant: Windscale, UK ...	$^{95}Zr—^{95}Nb$, ^{106}Ru	Whole body	10	$1.0\ 10^{-5}$	$1.0\ 10^{-4}$	$1.4\ 10^{-10}$	(5.0)		Table 73, paragraph 389
INTERNAL RADIATION									
Fuel reprocessing plants ..	^{3}H (airborne only)	Whole body	$2.0\ 10^{7}$	$6.3\ 10^{-12}$	$1.3\ 10^{-4}$	$3.5\ 10^{-10}$	(9.7)	$1.3\ 10^{-7}$	Table 74, paragraph 395
Doses calculated from recorded discharges or concentrations around a particular installation									
Reactors: Douglas Point, Canada	^{3}H (airborne only)	Whole body		$7\ 10^{-7}$ [d]					Paragraph 362

Bradwell, UK	^{65}Zn	Whole body	50	$1.1\ 10^{-6}$	$5.5\ 10^{-5}$	$3.3\ 10^{-12}$	(0.21)	Table 66, paragraph 358
Hinkley Point, UK	$^{134}Cs + ^{137}Cs$	Whole body	100	$9.1\ 10^{-7}$	$9.1\ 10^{-5}$	$6.2\ 10^{-12}$	(0.24)	Table 66, paragraph 358
Trawsfynydd, UK	$^{134}Cs + ^{137}Cs$	Whole body	100	$5.2\ 10^{-5}$	$5.2\ 10^{-3}$	$5.8\ 10^{-10}$	(0.39)	Table 66, paragraphs 356-358
Fuel reprocessing plants:								
Nuclear Fuel Services, USA	^{137}Cs	Whole body		$7.5\ 10^{-8}$ [e]				Table 72, paragraph 386
Windscale, UK ...	^{106}Ru, ^{144}Ce	Gonads	$2.6\ 10^{4}$	$1.6\ 10^{-9}$	$4.2\ 10^{-5}$	$5.9\ 10^{-11}$	(5.0)	Tables 72 and 73, paragraphs 387-389
	^{134}Cs, ^{137}Cs	Whole body			$3.0\ 10^{-2}$	$4.3\ 10^{-8}$	(5.0)	Table 73, paragraph 390

[a] The numbers are given with two significant figures for calculational purposes and not as an indication of accuracy.

[b] The load factor for the estimated installed capacity of 4300 GW(e) in the year 2000 has been assumed to be the same as that known to apply to the installed capacity of 20 GW(e) in 1970, namely 0.5. Doses resulting from ^{3}H and ^{85}Kr have been calculated for the year 2000 assuming that the quantity produced by fission (table 55) is discharged in its entirety. Doses which could result from other radio-nuclides discharged are not shown for the year 2000, because the quantities likely to be discharged cannot be predicted as they depend upon waste management policy.

[c] This list of local doses is incomplete; it includes only doses related to individual installations or to operations based on the total power generation rate for which either adequate data exist or reasonable assumptions can be made.

[d] The calculated dose applies to hypothetical individuals at or near the site boundary.

[e] The calculated dose applies to hypothetical adults eating locally caught fish.

TABLE 76. ESTIMATES OF WORLD-WIDE AVERAGE DOSE COMMITMENTS FROM MAN-MADE ENVIRONMENTAL RADIATION AND ANNUAL DOSES FROM NATURAL BACKGROUND

	Dose commitments (mrad)				*Annual doses from natural background[d] (mrad y^{-1})*	
	Atmospheric tests[a]	*Cratering experiments[b]*	*Electrical power production[c]* 1970	*Electrical power production[c]* 2000		
Gonads						
External	84	$1.7\ 10^{-2}$	$4.5\ 10^{-4}$	$0.5\ 10^{-1}$	72	(79)
Internal	35	$0.6\ 10^{-2}$	$4.7\ 10^{-4}$	$1.6\ 10^{-1}$	21	(22)
ROUNDED TOTAL	120	$2\ 10^{-2}$	$9\ 10^{-4}$	$2\ 10^{-1}$	93	(100)
Bone-lining cells						
External	84	$1.7\ 10^{-2}$	$4.5\ 10^{-4}$	$0.5\ 10^{-1}$	72	(79)
Internal	95	$0.6\ 10^{-2}$	$4.7\ 10^{-4}$	$1.6\ 10^{-1}$	20	(20)
ROUNDED TOTAL	180	$2\ 10^{-2}$	$9\ 10^{-4}$	$2\ 10^{-1}$	92	(99)
Bone marrow						
External	84	$1.7\ 10^{-2}$	$4.5\ 10^{-4}$	$0.5\ 10^{-1}$	72	(79)
Internal	76	$0.6\ 10^{-2}$	$4.7\ 10^{-4}$	$1.6\ 10^{-1}$	17	(17)
ROUNDED TOTAL	160	$2\ 10^{-2}$	$9\ 10^{-4}$	$2\ 10^{-1}$	89	(96)

[a] Dose commitments resulting from atmospheric tests carried out before 1971 (table 45). For ^{14}C, only the doses accumulated up to year 2000 were taken into account. The total dose commitment to the gonads and bone marrow due to ^{14}C is about 140 millirads, and that to cells lining bone surfaces is about 170 millirads.

[b] Dose commitments resulting from peaceful nuclear explosions conducted before 1972 (paragraphs 304, 306, and 307).

[c] Dose commitments per year of generation of electricity (1970 or 2000); summation of data in table 75.

[d] Taken from table 20. Estimates of the 1966 report are given in parentheses.

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