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EXPOSURES FROM MAN-MADE SOURCES OF RADIATION

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CONTENT

INTRODUCTION

1. The Committee has continually kept under review the exposures of the world population resulting from releases to the environment of radioactive materials from man-made sources. Exposures from such sources reviewed in the UNSCEAR 1993 Report [U3] included atmospheric nuclear testing, underground nuclear testing, nuclear weapons fabrication, nuclear power production, radioisotope production and uses and accidents at various locations. New information on man-made environmental exposures is considered in this document.

2. The testing of nuclear weapons in the atmosphere was the most significant cause of exposure of the world population to man-made environmental sources of radiation. The practice continued from 1945 to 1980. Although the testing has ceased and the Committee's assessment of global doses based on measured ^{90}Sr deposition remains an accurate evaluation of the resulting exposures, new data on the yields of individual tests have been made available. These allow more detailed calculation to be made of dispersal of radionuclides throughout the world following injection of debris into the atmosphere. Previous estimates of exposures from atmospheric testing were based on accumulated average doses (dose commitment), but there is interest as well in the annual doses received by individuals. Annual dose estimates are derived in this document and further considerations are made of exposures to individuals who lived in the local vicinities of the test sites.

3. Following the cessation of atmospheric testing, nuclear weapons continued to be tested underground, but since 1996 this practice has also been halted. Underground testing resulted only infrequently in releases of radionuclides to the environment and exposures of individuals. Beyond the testing of nuclear weapons, the military fuel cycle, involving the production of weapons materials and the fabrication of the devices, has also resulted in releases of radioactive materials to the environment. Information on exposures surrounding the industrial sites of nuclear materials production and weapons fabrication are considered in this document. Both historical and contemporary data are presented, if not previously reviewed by the Committee.

4. Nuclear power production continues in an increasing number of countries. Rather complete monitoring and reporting of radionuclides released, especially from nuclear reactors, provides adequate input of data for analysis of exposures from this source. Data on annual releases for the period 1990-1997 and analysis of longer-term trends are included in this document. Another continuing practice, radioisotope production and uses, involves rather trivial doses that can be only roughly estimated from the total size of the industry worldwide and some approximate figures on fractional releases of radionuclides produced. The Committee's previous assessment of these exposures would seem to remain valid.

5. Another source of exposures that may be considered to be man-made involves use of fuels or materials containing naturally occurring radionuclides. These are referred to as enhanced natural radiation exposures. It has been the practice of the Committee to evaluate these along with other exposures from natural radiation. These results are included in document R.578, "*Exposures from natural radiation sources*".

I. TESTING AND PRODUCTION OF NUCLEAR WEAPONS

6. The testing of nuclear weapons in the atmosphere, which took place from 1945 until 1980, involved large releases of radioactive materials to the environment and caused the largest collective dose thus far from man-made sources of radiation. Previous assessments by the Committee of the collective dose to the world population in the UNSCEAR 1982 and 1993 Reports [U3, U6] are complete and valid. In the latter Report [U3], transfer coefficients are given for the dose per unit release or per unit deposition density for over 20 radionuclides for inhalation, ingestion and external exposure pathways.

7. The evaluation of the collective dose from this practice has been based on the measured global deposition density of ^{90}Sr, limited measurements of ^{95}Zr deposition and on ratios of the other radionuclides to these. The annual depositions were measured in some detail during the time of this practice. This has meant that the collective doses could be calculated more directly and with less uncertainty than relying on estimates of the amounts of radionuclides produced in the tests and their dispersion in the environment.

8. In recent years some further details of atmospheric nuclear testing have become available. In particular, the numbers and yields of the explosions have been adjusted, and estimates are being made of the local doses to populations living in the vicinities of the test sites. This information will be taken note of by the Committee to complete the historical record of this practice.

9. In its previous assessments, the Committee placed emphasis on the estimation of the collective doses from atmospheric nuclear testing and has not evaluated in detail the annual doses. Approximate indication of the magnitudes of annual doses was presented in the UNSCEAR 1982 Report [U6]. The unfolding of collective doses to derive annual doses is presented below in more detail to illustrate the time dependence of contributions to the annual effective doses from various radionuclides and to estimate the residual dose rates received at present by the world population.

10. The production of nuclear weapons involves securing quantities of enriched uranium or plutonium for fission devices and of tritium and deuterium for fusion devices. The fuel cycle for military purposes is similar to that for nuclear electrical energy generation: uranium mining and milling, enrichment, fuel fabrication, reactor operation and reprocessing. Releases of radionuclides may occur at the various stages but particularly during reprocessing and plutonium separation. Initial information on exposures from operation of installations of the military fuel cycle was included in the UNSCEAR 1993 Report [U3]. Discharges and hence exposures were greatest during the earliest years of establishment of nuclear arsenals. Further data of mostly historical nature is summarized in this Chapter.

A. ATMOSPHERIC TESTS

1. Number and yield of tests

11. Further information on the number and yields of atmospheric nuclear tests has been reported by the countries that conducted the tests. In the UNSCEAR 1993 Report [U3] the number of tests by all countries was adjusted from 423 to 520. Although this is greater than a 20% increase, it now appears that the estimated total and fission yields will be revised downwards.

12. Compilations of data on atmospheric nuclear tests have been published within the last few years by the United States [D4], the former Soviet Union [M2], the United Kingdom [J3] and France [D3], listed here in chronological order of the publication dates. Information has been provided on the date of each test, the name or designation, location, type, purpose and the total explosive yield. In order to verify production amounts of important globally dispersed fission radionuclides, it would also be necessary to know the fission yield of each test or series of tests. Except for an incomplete listing by France, these data are unfortunately not yet available.

13. The data on atmospheric nuclear tests needed by the Committee for exposure evaluations are given in Table 1, and a summary for each country and each test site is provided in Table 2. The date, type and total explosive yield of individual tests are as reported in the country compilations. In a few cases, the total yields reported by the United States and the former Soviet Union were not specific, e.g. low, submegatonne, or within a designated range. In order to provide specific values for summations and analyses, estimates were made according to assumptions given in the footnotes in Table 1.

14. Assumptions are also needed to estimate the values of the fission and fusion yields of individual tests. Relatively low yield explosions may be assumed to be due to fission only, and very high yield explosions were thermonuclear tests with substantial fusion yields. For purposes of providing values for Table 1, all tests smaller than 0.5 Mt total yield have been assumed to be due only to fission, unless otherwise indicated. For tests in the range 0.5-10 Mt, fission yields of about 50% have reported to be representative [G4], and that value has been assumed here. There were 9 tests in the range 10-25 Mt. With no other indications available, fission yields of 33% were assumed in Table 1 for these tests.

15. The largest test of 50 Mt conducted by the former Soviet Union in 1961 was reported to have a fission yield of 3% and a fusion yield of 97% [M2]. Special design measures were taken to obtain such a high fusion yield. It would be desirable to have further information on the fission and fusion yields of atmospheric nuclear tests to substantiate the somewhat arbitrary assumptions that must otherwise be made. Because of the importance of a few large yield atmospheric nuclear tests to the fission, fusion and total yields, these are listed separately in Table 3. These 25 tests account for nearly 66% of the total explosive yield of all tests and 53% of the estimated fission yields. It would be of highest priority to have the fission yields of these tests verified.

16. The annual values of the number and yields of atmospheric tests by all countries are summarized in Table 4. These data are also illustrated in Figures I and II. The number of tests (Figure I) was greatest during 1951-1958 and 1961-1962. There was a moratorium in 1959, which was largely held as well in 1960. The predominant years of testing in terms of the total explosive yields (Figure II) were 1962, 1961, 1958 and 1954. The total number of atmospheric tests by all countries was 541, and the total yield was 440 Mt. The fission yield of all atmospheric tests is estimated at present to be 182 Mt.

17. A portion of the radioactive debris produced in atmospheric tests conducted on the earth's surface is deposited locally at the site of the test. This portion is estimated to correspond to 50% of the fission yield on average [P1]. The remainder and all of the debris of airbursts is widely dispersed in the atmosphere. Airbursts are defined as occurring at or above a height in metres of $55\ Y^{0.4}$, where Y is the total yield in kilotonnes [P1]. With the indication of the type of test given in Table 1, the apportionment of fission yield corresponding to local and more widespread tropospheric and stratospheric portions has been made in Tables 1, 2 and 4.

18. As indicated in the summary Tables 2 and 4, the locally deposited debris corresponds to 24 Mt. Therefore, 158 Mt is estimated to have received widespread dispersion, contributing to global fallout. This latter value inferred from yield information may be compared with the value of 155 Mt derived

from global ^{90}Sr measurements (604 PBq deposited worldwide divided by the production estimate of 3.9 PBq Mt^{-1}). The previously existing discrepancy between inferred and measured fission yields (189 Mt based on earlier fission yield estimates [B1, U6] compared to 155 Mt measured) has been eliminated with the new yield estimates for atmospheric tests.

2. Dispersion and deposition of radioactive debris

19. Nuclear weapons tests were conducted at various locations on and above the earth's surface, including mountings on towers, placement on barges on the ocean surface, suspensions from balloons, drops from airplanes and high-altitude launchings by rockets. Depending on the location of the explosion (latitude and altitude), the radioactive debris entered the local, regional or global environment. From extensive monitoring following individual tests and for the entire period of fallout input and deposition, considerable information was gained on the movement and mixing processes in the atmosphere. The radioactive debris served as tracer material in this respect.

20. A basic compartment diagram representing atmospheric regions and the predominant atmospheric transport processes is shown in Figure III. This was developed to describe atmospheric dispersion and deposition of radioactive debris produced in atmospheric nuclear testing [U6]. The atmosphere is divided into equatorial and polar regions from 0° to 30° and 30° to 90° latitude, respectively. The troposphere height is variable with latitude and season, but for modelling purposes it is assumed to be at an average of 9 km altitude in the polar region and 17 km in the equatorial region. The lower stratosphere is assumed to extend to 17 km or 24 km in the two regions and the upper stratosphere to 50 km in both regions. Only a few tests injected material above the upper stratosphere, designated the high atmosphere, which extends to several hundred kilometres to include the remainder of the region from which debris will eventually be deposited on the earth's surface.

21. Apportionment of debris in the atmosphere can be made based on stabilization heights of cloud formation following the explosion. Empirical values based on a number of observations are given in Table 5 [P1]. These results were used for the earlier estimates of fallout production from atmospheric testing that were quoted in the UNSCEAR 1982 Report [U6]. Adjustments can now be made according to the revised values of total yields and the fission yield estimates given in Table 1. The partitioned yield estimates are included in Tables 1 and 2, and a summary of annual injections into the various atmospheric regions is given in Table 6.

22. Aerosols in the atmosphere descend gravitationally at highest altitudes and are transported with the general air movements at lower levels. Eddy diffusion causes irregular migration of air masses in the general directions indicated in Figure III in the lower stratosphere and upper troposphere. The circular air flow pattern in the troposphere at lower latitudes is termed Hadley cell circulation. These cells increase or decrease in size and shift latitudinally with season. The mean residence time of aerosols in the lower stratosphere ranges from 3 to 12 months in the polar regions and 8 to 24 months in the equatorial regions. The specific seasonal values, determined from empirical fitting to fallout radionuclide measurements, are indicated in Figure IV. The most rapid removal occurs during the spring months. Removal half-times to the next lower region from the upper atmosphere of 6 to 9 months and from the high atmosphere of 24 months have been found to be representative [B1]. A removal half-time of infinity (∞) indicated in Figure IV means that no transfer takes place via the particular pathway during that season of the year.

23. An empirical atmospheric compartmental model based on Figures III and IV has been used to estimate surface air concentrations and deposition of fallout radionuclides starting with estimated

fission production yields of each test [B1]. With rather complete measurements of ^{90}Sr in air and deposition and uncertainties in reported fission yields, this modelling work has not been pursued. Improved estimates of fission yields changes this situation and allows the possibility of examining in greater detail the deposition of other radionuclides, such as ^{95}Zr and other short-lived emitters, and of projecting the measurement records beyond levels of detection capabilities.

24. The parameters of the empirical model were set with tracer radionuclides or those injected at limited times, such as ^{185}W, ^{109}Cd and ^{54}Mn, as well as with the longer-term records of ^{90}Sr. The fit of the calculation to the ^{90}Sr data in surface air is shown in Figure V for the northern hemisphere and Figure VI for the southern hemisphere. With the presently available estimates of fission yields of individual atmospheric tests, the model can match rather well the monthly data that show seasonal variations in the concentrations. The model indicates the total ^{90}Sr inventory in the hemispheric troposphere. This has been converted to a concentration with use of a volume parameter of 0.0001 Bq m^{-3} per PBq, empirically determined from the ^{90}Sr data for mid-latitude locations [B1]. A summary of annual average calculated and measured concentrations of ^{90}Sr in surface air of the mid-latitude regions is given in Table 7.

25. Measurements of ^{90}Sr in surface air were made routinely at a number of locations in the world. A global surface air monitoring network was maintained by the United States Naval Research Laboratory during 1957-1962 [L6] and continued by the Environmental Measurements Laboratory of the United States Department of Energy during 1963-1983 [F4]. The levels subsequently were undetectable with the methods used. The representative measured concentrations of ^{90}Sr in air shown in Figures V and VI are derived from averaging the results of several sites in the mid-latitudes of hemispheres (see footnotes to Table 7).

26. Some slight deviations in measured and calculated results of ^{90}Sr in air may be due to inaccurate estimation of injection amounts or of the initial partitioning of debris in the atmosphere or to variations in the measured results or in the meteorology that may occur from year to year. For example, the rapid depletion of the polar stratosphere in 1959 following the 1958 Soviet tests is notable, as is the absence of the peak in 1962 in the southern hemisphere following injections into the troposphere and stratosphere of the equatorial region from tests in that year.

27. Long-term monitoring of ^{90}Sr deposition has been reported in global networks operated by the Environmental Measurements Laboratory of the United States [H5] and the Harwell Laboratory of the United Kingdom [P3]. Quite comparable results have been obtained. The results of deposition densities at individual sites have been averaged within latitude bands and multiplied by the area of the bands to obtain estimates of the hemispheric and global deposition amounts. The annual results are shown in Figures VII and VIII for the northern and southern hemispheres, respectively, compared to the estimates derived from the atmospheric model. The agreement is quite close until the early 1980s when the uncertainties in the measurements began to increase.

28. The total record of monthly ^{90}Sr deposition from 1945 to 2000, calculated also for periods before and after the measurements were feasible, is shown in Figure IX. The deposition rate was generally about a factor of 5 greater in the northern hemisphere from 1953 to 1965 and from 1977 to 1983. During 1967-1977 and since 1985, approximately comparable fallout rates occurred in both hemispheres. A summary of the annual measured and calculated results of ^{90}Sr deposition is given in Table 7. Using the measurement results preferentially, when available, the global deposition of ^{90}Sr is estimated to be 588 PBq. This would indicate a decay of 4% of the injected amount of ^{90}Sr prior to deposition (158 Mt × 3.9 PBq Mt^{-1} = 616 PBq), corresponding to an average residence time of debris in the atmosphere of 1.8 years. The global cumulative deposit reached a maximum in 1967 of 456 PBq (Table 8). By the year 2000, this will decay to 240 PBq.

29. Because of preferential exchange of air between the stratosphere and troposphere in the mid-latitudes of the hemisphere and the air circulation patterns in the troposphere, there is enhanced deposition in the temperate regions and decreased deposition (by about a factor of two) in the equatorial and polar regions. The latitudinal distribution of ^{90}Sr deposition determined from the global measurements is given in Table 9. Since most of the atmospheric tests were conducted in the northern hemisphere, the deposition amounts are greater there than in the southern hemisphere.

30. With demonstrated accurate results obtainable with the empirical atmospheric model, the concentrations in air and deposition of other radionuclides can be calculated. Previously, estimates were made from ratios to ^{90}Sr values. The atmospheric model can take better account of decay prior to deposition and can start with the fission production values that are independent of estimates for other radionuclides. This may be particularly important for short-lived radionuclides that were inadequately monitored at the time the testing occurred.

31. An important component of the residual global contamination from atmospheric testing is ^{137}Cs. Because of the similarity in the half-time of ^{137}Cs (30.14 a) and ^{90}Sr (28.78 a), deposition occurs according to the ratio of fission yields: $^{137}Cs/^{90}Sr = 1.5$. Calculated deposition of ^{137}Cs is indicated in Table 8. The latitudinal distribution can be inferred from the pattern of ^{90}Sr (Table 9). Some of the levels in various latitudinal bands are illustrated in Figure X.

32. One further illustration of the calculated results is the annual deposition of ^{95}Zr, which is shown in Figure XI. With a half-life of 64 days, ^{95}Zr has been used as an indicator of deposition of other short-lived radionuclides. This can be done more accurately with better estimates of the record of ^{95}Zr deposition. Alternatively, the deposition of each radionuclide can be calculated separately. Such refinements in the analysis of radionuclide production, dispersion and deposition from atmospheric nuclear testing will continue to be made in revisions of this document. It is not expected that estimates of exposure will be greatly altered, as the main components have been well established by the substantial monitoring results that the Committee has reviewed and that form the basis of the exposure estimates.

3. Regional and global annual doses

33. The Committee previously provided a rough indication of the annual doses from fallout radionuclides in the UNSCEAR 1982 Report [U6]. For the period 1958-1979, the maximum dose rate was estimated to be 0.14 mSv a^{-1} in 1963, and it had decreased by almost an order of magnitude by 1979. With available empirical models, unfolding of the collective dose can be extended and undertaken in much more detail. The results of this exercise are presented in this Section.

34. The basic input to dose calculations from fallout radionuclides is the measured ^{90}Sr deposition density. The global, population-weighted average annual deposition densities are listed in Table 10 through 1985. By then the stratospheric inventory from atmospheric tests was largely depleted. Some of the monitoring sites were affected by the Chernobyl accident in 1986. Subsequently, a low, constant level of deposition has been measured that reflects resuspended soil particles [A4, I5]. Other longer-lived radionuclides in global fallout have also been monitored, but these have been found to be present in relatively constant ratios to ^{90}Sr. For short-lived radionuclides (half-life <100 d) decay prior to deposition may be significant. For these radionuclides the pattern of deposition has been taken to be that of ^{95}Zr, with the magnitude estimated from the average value of the ratio determined by available measurements. Henceforth, the calculated deposition of short-lived radionuclides may be used in the exposure evaluations.

35. The transfer coefficients P_{25} used to evaluate the effective dose committed by unit deposition density of a radionuclide were given in the UNSCEAR 1993 Report (Table 8, page 127) [U3]. For the external irradiation pathway, the initial effective dose rate per unit deposition density [derived from the dose rate in air per unit deposition density [B2] times the dose rate in air to effective dose conversion factor (0.7) times the occupancy-shielding factor (0.2 fractional time outdoors + 0.8 fractional time indoors × 0.2 building shielding = 0.36)] has been multiplied by the mean residence time of the radionuclide ($1/\lambda = 1.44T_{½}$). This reflects the time dependence of the dose rate, namely

$$\int_0^\infty D_0 e^{-\lambda t} dt = D_0/\lambda \quad (1)$$

where D_0 is the dose rate at the time of deposition and λ is the radioactive decay constant for the radionuclide. For annual components of the transfer coefficient, the integration limits are one year intervals. Thus, for the first year following a specified deposition amount, the annual dose is

$$\int_0^1 D_0 e^{-\lambda t} dt = D_0(1 - e^{-\lambda})/\lambda \quad (2)$$

The subsequent annual dose component is that from the previous year times $e^{-\lambda}$.

36. Of the radionuclides contributing to external exposure, only ^{137}Cs has a half-life greater than a few years. For this radionuclide the depth distribution in soil has been taken to correspond to a relaxation length of 3 cm. For the other radionuclides, a surface, plane source distribution is assumed. The parameters required to calculate the annual effective doses from external irradiation are summarized in Table 11.

37. For the inhalation pathway, exposures depend on the concentrations of radionuclides in air, but because of the association between concentrations in air and deposition densities through the deposition velocity, the transfer coefficients for the dose from inhalation can be given in terms of the measured deposition density of ^{90}Sr and the ratios of the deposition of radionuclides to that of ^{90}Sr. These transfer coefficients, P_{25}, were given in the UNSCEAR 1993 Report (Table 8, page 127) [U3]. The dose from inhalation can be assumed delivered in the same year that the deposition occurred. Subsequent exposures from resuspension are accounted for in the measured air concentrations and the derived deposition velocity, and although these exposures may continue in a few further years, it does not involve much error to include all of the exposure in the year of initial deposition. The parameters required to calculate the annual effective doses from inhalation are given in Table 12.

38. For the ingestion pathway, exposures from the longer-lived radionuclides ^{90}Sr and ^{137}Cs may be related to the measured deposition density of ^{90}Sr (the ^{137}Cs to ^{90}Sr ratio of 1.5 is used to derive the deposition density of ^{137}Cs) by empirical transfer models with parameters evaluated from regression fits to the measured concentrations of these radionuclides in diet and the human body. These models apply to continuing deposition throughout the year, as occurred during fallout deposition. Thus, the seasonal variability in transfers to diet is averaged out in a single annual value.

39. The model used to describe transfer of ^{90}Sr or ^{137}Cs from deposition to diet is of the form:

$$C_{d,i} = b_1 F_i + b_2 F_{i-1} + b_3 \sum_{n=1}^{\infty} e^{-\lambda' n} F_{i-n} \quad (3)$$

where $C_{d,i}$ is the concentration of the radionuclide in a food component d or in the total diet in the year i due to the deposition density rate in the year i, F_i, in the previous year, F_{i-1}, and in all previous years, reduced by exponential decay. The exponential decay with decay constant λ' reflects both radioactive decay and environmental loss of the radionuclide. The coefficients b_i and the parameter λ' are determined by regression analysis of measured deposition and diet data. The coefficients b_i represent the transfer per unit annual deposition in the first year (b_1), primarily from direct deposition, in the second year (b_2) from lagged use of stored food and uptake from the surface deposit and in subsequent years (b_3) from transfer via root uptake from the accumulated deposit.

40. The transfer from diet to the human body (bone) for ^{90}Sr is described in a two component model:

$$C_{b,i} = c\,C_{d,i} + g\sum_{m=0}^{\infty} e^{-\lambda_b m} C_{d,i-m} \qquad (4)$$

where $C_{b,i}$ is the concentration of ^{90}Sr in bone in the year i, c is a coefficient for short-term retention and g is a coefficient for longer-term retention with removal governed by the decay constant λ_b. The parameters c, g and λ_b are determined by regression fits to monitoring data.

41. The retention of ^{137}Cs in the body is relatively short-term (retention half-time of around 100 d). Therefore, the annual dose per unit intake can be expressed by a single transfer coefficient P_{34} that applies to the year of intake. The annual doses from ^{90}Sr and ^{137}Cs in the body are evaluated with use of the transfer coefficient P_{45}. The values of the transfer coefficients used in the calculation of the annual effective dose from ingestion of ^{90}Sr and ^{137}Cs are given in Table 13.

42. Further exposure via ingestion of longer-lived radionuclides occurs from ^{55}Fe and the transuranium elements. The doses committed from the latter radionuclides are very small, and the contributions to annual doses are negligible. A transfer model does not exist for ^{55}Fe. Its half-life is only 2.74 years; therefore, it is arbitrarily assumed that 80% of the committed dose is delivered in the first year following deposition and the remainder in the following year.

43. For the short-lived radionuclides ($T_{½}$ <100 d), the dose from all pathways occurs essentially within the first year during and following deposition. While the committed doses have been derived from relationships to the cumulative deposition density of ^{95}Zr, the annual doses cannot be thus derived because the annual record of ^{95}Zr deposition is not complete. Provisionally, the committed doses from these radionuclides have been distributed into annual amounts in proportion to the fission yields of the nuclear tests. In revisions of the document, the calculated depositions will be used to estimate annual doses. Some of the radionuclides (^{54}Mn, ^{55}Fe, Pu, ^{241}Am) are produced more prominently in fusion explosions; the doses for these can be distributed according to the annual fusion yields, or these too can be calculated with good accuracy. The committed doses from short-lived radionuclides, from which the annual doses are calculated, are given in Table 14.

44. The annual doses from tritium have been evaluated using the seven compartment model presented by the United States National Council on Radiation Protection and Measurements [N1]. With volumes and transfer rates applicable for the hydrological cycle of the world and intake of water by man assumed to be 33% from the atmosphere, 53% from surface fresh waters, 13.3% from groundwater and 0.7% from ocean surface water (through fish) [N1], the dose per unit release is 0.057 nGy PBq^{-1}. Further details of the model are presented in document R.582, *"Dose assessment methodologies"*.

45. The annual doses from ^{14}C have been derived with use of the multicompartment model described in document R.582, "*Dose assessment methodologies*". The estimates are only approximate, since

widespread, immediate mixing in large regions is assumed in the model formulation. The annual effective doses from ^{14}C produced in atmospheric nuclear testing was at maximum 7.7 μSv in 1964 and has decreased by a factor of 4 subsequently. The dose would be estimated to be somewhat less when account is taken of the input of stable carbon into the atmosphere from fossil fuel burning, thus diluting the ^{14}C.

46. The estimates of the annual doses from radionuclides in fallout from atmospheric nuclear testing are presented in Table 15. These results are based on the global, population-weighted average deposition of fallout radionuclides. The doses for more specific regions of the world may be obtained by adjusting to the latitudinal distribution of ^{90}Sr deposition (Table 9). In the northern hemisphere the annual doses are higher by a factor of 1.1 (hemispheric average) and 1.6 (temperate zone, 40°-50°) and in the southern hemisphere lower by a factor of 0.3 (hemispheric average) and 0.5 (temperate zone, 40°-50°) compared to the global average.

47. The estimated annual doses resulting from atmospheric nuclear testing are illustrated in Figures XII and XIII. The annual dose was highest in 1963 (0.16 mSv) and has subsequently declined to less than 0.01 mSv in the 1990s. The short-lived radionuclides made important contributions to the annual doses at the time of the explosions. Doses from the ingestion pathway peaked in 1964 and from external irradiation in 1965. The annual doses at present are due primarily to external irradiation (70%). The dose from ^{14}C now exceeds that from ingestion of other radionuclides. The doses at future times are also given in Table 15.

4. Local exposures

48. Since atmospheric nuclear tests were conducted in relatively remote areas, exposures of local populations did not contribute significantly to the collective dose from this practice. Nevertheless, those individuals living downwind of the test sites received greater than the average doses. Efforts are continuing to reconstruct the exposure conditions and to estimate the local doses. Available information was presented in the UNSCEAR 1993 Report [U3], and this is summarized in Table 16. Further results are presented in this Section. The data are still not systematic and complete. It will be necessary to add further details as the dose reconstruction efforts progress.

49. The locations of several test sites are shown in maps in Figures XIV, XV and XVI. The areas within a few hundred kilometres surrounding the site are generally said to be local and those within a few thousand kilometres to be regional. Delineations of 500 km and 1000 km distances from the test sites are shown in the figures for reference purposes. Exposed populations are only those living in downwind, generally eastward, directions.

[Inclusion of additional maps will be considered in the revision of this document.]

(a) Nevada test site

50. The Nevada test site in the United States was the location for 84 atmospheric nuclear tests; 81 tests were conducted during 1951-1958, and 3 further tests were performed in 1962. Local areas were affected by a relatively few tests, but more significantly so on these occasions than more distant areas of the United States, which received less deposition and exposure, but were more evenly affected by a larger number of tests. The external exposures to local populations were estimated at the time of testing to be low, however concerns of the public on the health impact of the exposures grew. As a consequence, rather detailed dose reconstruction projects were undertaken in the 1980s.

51. Estimates of external exposures from atmospheric tests at the Nevada test site were reported by Anspaugh et al. [A1, A3]. Results were derived from survey metre and film badge measurements for 300 communities in the local areas (<300 km) surrounding the test site in Nevada and in southwestern Utah. The distribution of individual cumulative exposures is given in Table 17. The effective dose exceeded 3 mSv in 20% of the population of 180,000. The highest effective doses were in the range 60-90 mSv, and the population-weighted value was 2.8 mSv [A1]. The exposures resulted primarily from short-lived gamma emitters (half-lives <100 d). The estimates were based on outdoor occupancy of 50% and building shielding factor of 0.5; the usual UNSCEAR assumptions are 20% and 0.2, respectively. Most of the exposures resulted from relatively few events; 90% of the cumulative collective exposure of 470 man Sv resulted from 17 events, the most significant being the test Harry of 19 May 1953 (180 man Sv), test Bee of 22 March 1955 (70 man Sv) and test Smoky of 31 August 1957 (50 man Sv) [A3].

52. Internal exposures resulting from atmospheric testing at the Nevada test site have been estimated from deposition measurements and an environmental transfer model [K2, W2]. Absorbed doses to organs and tissues from internal exposure were substantially less than from external exposure, with the exception of the thyroid in which ^{131}I from ingestion of milk contributed relatively higher doses. Estimates of absorbed doses in the thyroid of 3545 locally exposed individuals ranged from 0 to 4.6 Gy; the average was 98 mGy and the median 25 mGy [T4]. Only five individuals received absorbed doses greater than 3 Gy, and all of them drank milk from a family-owned goat [T4]. An extensive study has been completed by the National Cancer Institute of the United States of thyroid doses in all counties of the country from ^{131}I deposition following the atmospheric tests in Nevada [B6]. The per capita thyroid doses ranged up to 100 mGy in local areas. For the entire population of the United States the estimate was 20 mGy with a collective absorbed dose of 4 10^6 man Gy.

(b) Bikini, Enewetak test sites

53. An extensive nuclear test programme was conducted by the United States at locations in the Pacific (Table 1). The most significant test resulting in local exposures was the thermonuclear test Bravo of 28 February 1954 at Bikini Atoll. Unexpectedly heavy fallout occurred in the local area eastward of the Atoll (Figure XIV). Within a few hours of the explosion, fallout particles descended on Rongelap and Ailinginae Atolls, located 200 km from Bikini, exposing 82 persons. The Japanese fishing vessel, Lucky Dragon, was also in this area, and 23 fishermen were exposed. Farther east, exposures occurred at Rongerik Atoll (28 United States servicemen) and Utrik Atoll (159 persons). These individuals were evacuated within a few days of the initial exposures.

54. External exposures from the Bravo test, mainly from short-lived radionuclides, ranged from 1.9 Sv on Rongelap (67 persons, including 3 *in utero*), 1.1 Sv on Ailinginae (19 persons, including 1 *in utero*) and 0.1 Sv on Utrik (167 persons, including 8 *in utero*) [L4]. The collective dose from these exposures received by these individuals before evacuation was, thus, 160 man Sv. Thyroid doses, resulting from several isotopes of iodine, tellurium and by external gamma radiation, were estimated to be 12 Gy on average (42 Gy maximum) to adults, 22 Gy (82 Gy maximum) to children of 9 years and 52 Gy (200 Gy maximum) to infants of 1 year [L4].

55. The external exposure resulting from the Bravo test to the servicemen on Rongerik Atoll was 0.8 Sv [L4]. For the 23 Japanese fishermen, the external exposures from the fallout deposition on the deck ranged from 1.7 to 6 Sv, mostly received on the first day of the fallout but continuing for 14 days until the ship arrived in its port [C9]. The thyroid doses to the fishermen were estimated to have been 0.2-1.2 Gy from ^{131}I, based on external counting, but since other short-lived iodine isotopes were also present, the total doses to the thyroid for inhalation during a period of 5 hours were estimated to have been 0.8-4.5 Gy [C9].

56. There seems to have been no other tests that caused significant exposures to the population in the Pacific region. Exposures to residual radiation levels on Utrik and Rongelap Atolls to residents who returned to these islands in 1954 and 1957, respectively, were of the order of 20-30 mSv over the following 20-year period from external irradiation and 20-140 mSv from internal exposure [C9]. A radiological survey of residual radiation levels, primarily due to global fallout deposition, was conducted throughout the Marshall Islands in 1994 [S2], and more detailed surveys have been made of Bikini and Enewetak Atolls, which were evacuated prior to the testing, in order to evaluate eventual permanent resettlement [I4, R1]. During temporary resettlement of Bikini Atoll during 1971-1978, total whole-body exposures were estimated to be 2-3 mSv a^{-1} [G5]. Tests at other locations in the Pacific (Christmas Island and Johnston Island) were conducted in the high atmosphere with little local fallout deposition.

(c) Semipalatinsk test site

57. The Semipalatinsk test site is located in the northeast corner of Kazakhstan (see map in Figure XV). At this location, 456 nuclear tests were conducted, including 86 atmospheric and 30 surface tests [M2]. Kazakh authorities place the total number of tests at 470, including 90 atmospheric, 26 surface and 354 underground tests [K7]. Apparently, several failed tests, i.e. no nuclear yield, are included in the latter total [G8]. The most affected local populations lived northeast of the test site in the Semipalatinsk region of Kazakhstan and the Altai region of the Russian Federation.

58. Two tests were most significant in causing exposure of the population of Kazakhstan: the first test on 29 August 1949 and the first thermonuclear test on 12 August 1953. These and two other tests (24 September 1951 and 24 August 1956) contributed 85% of the total collective effective dose [G8]. Estimates of accumulated effective doses are listed in Table 18. Relatively high effective doses, in the range 2-4 Sv are estimated at several locations. Absorbed doses in the thyroid were estimated to be 1.3 Gy to adults and 6.5-13 Gy to children following the test of 29 August 1949 at Dolon, Cheremushky and Mostik. The population data and the collective dose estimates are not yet complete.

59. The Altai region of the Russian Federation is at a distance of about 200 km from the Semipalatinsk test site. This population was exposed following 48 explosions, with some contamination from an additional 10 tests [G1, L2]. The most significant exposure was caused by the nuclear test of 29 August 1949 [L1]. Effective doses received by the population from this explosion exceeded 2 Sv in some locations [L3]. Estimates of effective dose from external exposures in settlements most affected are given in Table 19. Account has been taken of indoor occupancy and building shielding (assumptions not specified) [L5]. As a general rule, the total effective dose (including internal exposure) was approximately twice the effective dose from external exposure alone [L4]. The absorbed dose to the thyroid for children (0-7 years) and adults following the same test are also specified in Table 19. The nuclear test of 7 August 1962 caused particularly high internal exposures from iodine radioisotopes [G2]. Absorbed doses in thyroids of children at certain locations were as high as 20 Gy.

60. The distribution of effective dose among the locally affected population surrounding the Semipalatinsk test site is not yet clear. Tsyb et al. [T1] indicated a population of 10,000 received a collective effective dose of 4,600 man Sv (Table 16). The collective effective dose from external exposure in all districts of the Altai region was reported by Logachev [L5] to be 11,000 man Sv. From the population of these districts the average external effective doses can be derived. These data are presented in Table 18. Not all districts were included, but the totals for the entire region were specified. Discrepancies are evident between Tables 18 and 19, with lower average effective doses in the regions than in the settlements, e.g. 280 mSv in Lokot settlement and 59 mSv in Lokot region. The difficulties of the dose reconstruction efforts will no doubt leave considerable uncertainties in the results, however when this work is completed, it is hoped that more definitive and consistent values will be available.

(d) Novaya Zemlya test site

61. The test site Novaya Zemlya in the Russian Arctic is large and remote. Although an extensive atmospheric test programme was conducted there, most of the tests were carried out at high altitudes, thus minimizing local fallout. There was one test of 32 kt yield on the land surface on 7 September 1957 [M2]. In addition, there were 2 tests on the water surface and 3 tests underwater at the site. Research programmes to investigate residual contamination both on and off site have been initiated. It may be that reindeer herders and those who consume reindeer meat have received low internal exposures primarily from ^{137}Cs that could be attributed to tests at this site.

(e) Maralinga, Emu test sites

62. The nuclear weapons testing programme of the United Kingdom included 21 atmospheric tests at sites in Australia and the Pacific. The tests in the Pacific at Malden and Christmas Islands in 1957 and 1958 were airbursts over the ocean (6 tests of submegatonne and megatonne yields) or explosions of devices suspended by balloons at 300-450 m over land (1 test of 24 kt and 2 tests each of 25 kt yield) [D2]. Local fallout would have been minimal following those tests. Twelve tests were conducted during 1952-1957 at three sites in Australia: Monte Bello Islands, Emu and Marailinga, the locations of which are shown on the map in Figure XVI. These were mainly surface tests of 60 kt yield or less. For each of these tests, trajectories of the radioactive cloud were determined, and monitoring of air and deposition locally and countrywide was performed [W1]. Estimates of external exposures in local areas were not made for the earlier tests; for tests of 1956-1957 the external effective doses were less than 1 mSv [W1]. The sizes of local populations were not indicated. Estimates also of internal exposures were made for the entire Australian population. The average effective dose was 70 μSv, and the collective effective dose was 700 man Sv in this population [W1]. A number of safety tests were conducted at the Maralinga and Emu sites in south Australia, resulting in the dispersal of ^{239}Pu over some hundreds of square kilometres. The potential doses to local inhabitants of these areas have been evaluated [D1, H2, W3].

(f) Mururoa, Fangataufa test sites

63. The French nuclear testing programme began with 4 low-yield surface tests at a site near Reggane in the Algerian Sahara in 1960-1961 [D3]. There is no information on local exposures following these tests. The subsequent programme was conducted at the uninhabited atolls of Mururoa and Fangataufa in French Polynesia in the South Pacific. Most of these involved detonation of devices suspended from balloons at heights of 220-500 m [D3], thus limiting local fallout production. Radiological monitoring has been conducted at surrounding locations. The closest inhabited atoll is Tureia (140 persons) at a distance of 120 km to the north; only 5000 persons lived within 1000 km of the test site. A larger population at Tahiti (84,000 persons in 1974) is located 1200 km to the northwest. Under normal prevailing conditions at the test site, radioactive debris comprising local and tropospheric fallout was carried to the east over uninhabited regions of the Pacific. On occasions, however, some material was transferred to the central South Pacific within a few days of the tests by westerly moving eddies. French scientists [B8] have identified five tests, following which regional population groups were more directly exposed (Table 20). A single rain-out event caused exposures in Tahiti after the test of 17 July 1974. Exposures resulted mainly from external irradiation from deposited radionuclides. Milk production on Tahiti provides only about 20% of local needs, and consumption is low, which limits ingestion exposures. Estimated effective doses to maximally exposed individuals after all five events were in the range 1-5 mSv in the year following the test. Some exposure would have persisted in the following years, but the dose estimates are not underestimated, since maximum individual doses were estimated. The collective effective dose of 70 man Sv may be a reasonable estimate for all local exposures at this test site. Estimates of exposures were made on a wider basis of measurements beginning in 1982. In

that year the external exposures in the region were in the range 1-10 μSv a^{-1}, internal exposure 2-32 μSv a^{-1} and total exposure 3-33 μSv a^{-1}, due mostly to residual ^{137}Cs deposition arising from global fallout. The collective effective dose was estimated to be about 1 man Sv in 1982 for all of French Polynesia [R2].

(g) Lop Nor test site

64. The Chinese nuclear weapons testing programme was carried out at the Lop Nor test site in western China shown on the map in Figure XV; 22 atmospheric tests were conducted between 1964 and 1980. Limited information is available on local deposition following the tests. Balloons were used to follow the trajectory of the debris clouds, and airborne and ground-based instruments were used to monitor the radiation levels. Estimates of exposures were made over a downwind area to a distance of 800 km [Z1]. Estimates of external exposures in cities or towns within 400-800 km from the test site in Gansu Province ranged from 0.02 to 0.11 mSv (Table 21) with an average of about 0.04 mSv for 3 tests, which accounted for over 90% of the dose from all Chinese tests [Z1]. Indoor occupancy of 80% and a building shielding factor of 0.2 were assumed. The relevant populations size in the area is not known.

[Further data are needed to complete a more systematic review of local exposures from atmospheric nuclear testing.]

B. UNDERGROUND TESTS

65. Testing of nuclear weapons underground began in 1951 by the United States and in 1961 by the former Soviet Union. Following the limited nuclear test ban treaty of 1963, banning atmospheric tests, both countries conducted extensive underground test programmes. The United Kingdom participated with the United States in a few joint underground tests. Underground test programmes of France and China continued until 1996, and India conducted a single underground test in 1974. A comprehensive test ban treaty was formulated in 1996, and while not yet ratified by all countries or entered into force, it would appear that the practice of underground weapons testing has also ceased.

66. The number of underground tests (Figure I) has greatly exceeded that of atmospheric tests, but the total yield (Figure II) of the tests has been much less. The largest underground tests were of reported yield 1.5-10 Mt (9 December 1973 at Novaya Zemlya) by the former Soviet Union [M2] and less than 5 Mt (6 November 1971 at Amchitka, Alaska) by the United States [D4], but most tests have been of much lower yield, particularly if containment of nuclear debris was desired. Only with venting or diffusion of gases following the tests, as has happened on occasions, could exposures of local populations occur.

67. A summary of underground test programmes and estimation of resultant exposures were presented in the UNSCEAR 1993 Report [U3]. There is no further information that could allow exposure estimates to be improved. It would be desirable to have a more complete list of those tests in which venting occurred and estimates of the amounts of radioactive materials thereby dispersed in the atmosphere. Thirty-two underground tests conducted at the Nevada test site were reported to have led to off-site contamination as a result of venting [H3]. Similar information is required for tests conducted by the former Soviet Union, France and China.

68. The number of underground tests requires revision, based on recently published information [D4, M2]. Several tests involved simultaneous detonation of nuclear charges, either in the same or in

separate bore-holes or tunnels. These so-called salvo tests were done for reasons of efficiency or economy, but they also deterred detection from distant seismic measurements. These tests usually involved 2 to 4 charges; the maximum number was 8. Since each charge has now been identified, they can be properly specified as separate tests. The annual numbers of underground tests conducted by each country are given in Table 22. The total number of tests by all countries is 1867.

69. The yields of individual underground tests have not been directly specified. Many are simply reported to be within a range of energies, for example <20 kt or 20-150 kt. The annual yields of underground tests at all locations have been compiled by the National Defence Research Establishment in Sweden [N6]. These estimates were included in the UNSCEAR 1993 Report [U3]. The total yield for all tests conducted through 1992 was 90 Mt. The yields of subsequent tests have not altered this total amount. The total yield of all underground tests conducted by the former Soviet Union has been reported to be 38 Mt [M2]. The yields apportioned to other countries are listed in Table 23.

70. ***Summary: all nuclear tests***. Table 23 provides a summary listing of all nuclear weapons tests, both atmospheric and underground. The total number of tests was 2,408; this includes the two combat explosions of nuclear weapons in Japan and a number of safety tests. The latter were of no nuclear yield, but they are conventionally included in listings of nuclear tests. The total yield of all tests was 530 Mt.

C. PRODUCTION OF WEAPONS MATERIALS

71. In addition to weapons testing, radionuclide releases also occurred from the installations where nuclear materials were produced and the weapons fabricated. Local and regional populations were thereby exposed. Some information on this practice was presented in the UNSCEAR 1993 Report [U3]. Especially in the earliest years of this activity, the pressures to meet production schedules and the lack of stringent waste discharge controls resulted in higher local exposures than in subsequent periods. Efforts are being made to evaluate the exposures that occurred during all periods of operation of these installations. Systematic evaluation of all such exposures may not be possible, but newly acquired information will be summarized in this Section. Present activities at some sites now also involve dismantling of weapons.

1. United States

72. Nuclear weapons plants in the United States included Fernald in Ohio (materials processing), Oak Ridge in Tennessee (enrichment, separations, laboratories), Rocky Flats in Colorado (manufacture of weapons parts), Hanford in Washington (plutonium production) and Savannah River in South Carolina (plutonium production). There are many more sites at which such operations were conducted and wastes were stored or disposed. It has been estimated that there are some 5000 locations in the United States where contamination with radioactive materials have occurred, not all of which are associated with weapons materials production [W4]. Estimates of releases of radioactive materials during the periods of operation of the nuclear installations are summarized in Table 24. Also listed are the exposures estimated to have been received by the local populations. This information might be extended when present studies are concluded, thus documenting better the historical exposures from this practice.

2. Russian Federation

73. There were three main sites of weapons material production in the former Soviet Union: Chelyabinsk, Krasnoyarsk and Tomsk. Relatively high releases occurred during the early years of

operation of these facilities. In additions, accidents have contributed to the background levels of contamination and to exposures of individuals living in the local and regional surroundings.

(a) Chelyabinsk

74. The Mayak nuclear materials production complex is located in the Chelyabinsk region between the towns of Kyshtym and Kasli near the eastern shore of Lake Irtyash. Operations began in 1948 of uranium-graphite reactors for plutonium production and a reprocessing plant. Relatively high discharges of radioactive materials to the Techa River occurred during 1949-1956 [D5]. Available information on exposures to the local population was summarized in the UNSCEAR 1993 Report [U3].

75. Estimates of releases of radionuclides during the early years of operation of the Mayak complex are presented in Table 25. Controls of releases, initially absent, were introduced in the early 1960s. The maximum releases in airborne effluents, primarily ^{131}I, occurred during 1949-1956 [D6]. During the same period, substantial releases of radionuclides were made into the Techa River [D5, K3]. Of the 100 PBq released during 1949-1956, 95 PBq were released during 1950-1951. Along with the fission products listed in Table 25, plutonium isotopes were also released.

76. The most highly exposed individuals from the releases to the Techa River were residents of villages along the riverbank, who used the water for drinking, fishing, waterfowl breeding, watering of livestock, irrigation of gardens, bathing and washing. In April-May 1951, a heavy flood resulted in contamination of the floodplain used for livestock grazing and hay making. The collective dose to the most exposed population during 1949-1956 was 6,200 man Sv (Table 26). Doses from external irradiation decreased in 1956 when residents of the upper reaches of the river moved to new places of residence and the most highly contaminated part of the floodplain was enclosed. For some inhabitants, however, the Techa River contamination has remained a significant source of exposure up to the present time.

77. On 29 September 1957, a fault in the cooling system of a storage tank containing liquid radioactive wastes led to a chemical explosion and a large release of radionuclides. The total activity dispersed off-site over the territory of the Chelyabinsk, Sverdlovak and Tyumen regions was approximately 74 PBq. The composition of the release is indicated in Table 25. Although the release was characterized mainly by rather short-lived radionuclides (^{144}Ce, ^{95}Zr), the long-term hazard was due primarily to ^{90}Sr. An area of 23,000 km^2 was contaminated at levels of ^{90}Sr greater than 3.7 kBq m^{-2} [N8]. In 1957, 273,000 people lived in the contaminated area. Of them, 10,000 lived where the ^{90}Sr deposition density exceeded 74 kBq m^{-2} and 2,100 where the levels were over 3,700 kBq m^{-2}. In areas exceeding ^{90}Sr contamination of 74 kBq m^{-2}, the population was evacuated. The main pathways of exposure following the accident were external irradiation and internal exposure from consumption of local food products.

78. Further exposure of the local population associated with operation of the Mayak complex occurred in 1967, when water receded from Lake Karachay and the wind caused resuspension of contaminated sediments from the shoreline. The lake had been used for waste disposal. The dispersed material, about 0.022 PBq, consisted mainly of ^{137}Cs, ^{90}Sr and ^{144}Ce (Table 25). The contaminated area, defined by levels of ^{90}Sr greater than 3.7 kBq m^{-2} and ^{137}Cs greater than 7.4 kBq m^{-2}, extend to a distance of 75 km from the lake. Approximately 40,000 people lived within this area of 2,700 km^2. The exposures from external irradiation and consumption of local foods were considerably less than those following the 1957 accident.

79. Present levels of exposures associated with operation of the Mayak complex have been estimated from the residual contamination [K4]. For internal exposure, average (and range) of consumption of food were determined to be milk 0.7 (0.5-1.0) kg d^{-1}, meat 0.14 (0.09-0.18) kg d^{-1}, bread 0.36 (0.27-0.52) kg d^{-1}, potatoes 0.57 (0.2-1.0) kg d^{-1}, vegetables 0.24 (0.14-0.43) kg d^{-1}, fish 0.05 (0.03-0.11) kg d^{-1}, mushrooms 0.02 (0.01-0.03) kg d^{-1} and berries 0.04 (0.01-0.06) kg d^{-1} [K4]. These values were used with concentrations given in Table 27 to estimate the average internal dose of 0.1 mSv a^{-1}. Average external exposure is estimated to be 0.01 mSv a^{-1}. With reference to a population of 320,000 surrounding the Mayak complex, the annual collective effective dose from present operations (1993-1996) is estimated to be 35 man Sv (Table 28).

(b) Krasnoyarsk

80. The Krasnoyarsk nuclear materials production complex is located about 40 km from the city of Krasnoyarsk. The first direct-flow reactor at Krasnoyarsk was commissioned in 1958, the second reactor in 1961 and the third closed-circuit reactor in 1964. A radiochemical plant for irradiated fuel reprocessing was put into operation in 1964. In 1985, a storage facility for spent fuel assemblies from reactors in Russia and Ukraine was put into service. There are plans to reprocess this fuel from the civilian nuclear fuel cycle in the future at the Krasnoyarsk site.

81. Radioactive wastes discharges from the Krasnoyarsk complex enter the Yenisei River. Trace contamination can be found all the way from the city of Krasnoyarsk to its estuary at a distance of about 2000 km [V1]. An estimate of the collective dose from radioactive discharges of the Krasnoyarsk complex during the period 1958-1991 is presented in Table 26 [K5], derived from data on the content of radionuclides in water, fish, floodplain and other components of the river ecosystem [N9, V1]. On the whole, the collective dose was about 1,200 man Sv. A major contribution to this dose was due to fish consumption (70%) [K6]. External exposure from the contaminated floodplain accounted for 17% of the collective dose. The main radionuclides contributing to the internal dose from fish consumption were ^{32}P, ^{24}Na, ^{54}Mn and ^{65}Zn. A major contribution to the external dose (over 90%) was due to gamma-emitting radionuclides, primarily ^{137}Cs, ^{60}Co and ^{152}Eu. Individual doses to the population varied over a wide range from 0.05 to 2.3 mSv a^{-1}. A major portion of the collective dose (about 84%) was received by the population living within 350 km of the site of radioactive discharges.

82. In 1992, two of three reactors of the Krasnoyarsk complex were shut down. This reduced considerably the amount of radioactive discharges to the Yenisei River, and the annual collective dose to the population was decreased by over a factor of 4. Present estimates of average doses (1993-1996) are 0.03 mSv a^{-1} (external), 0.02 mSv a^{-1} (internal). With a local population of 200,000, the annual collective effective dose is estimated to be 10 man Sv (Table 28).

(c) Tomsk

83. The Siberian nuclear materials production complex is located in the town of Tomsk-7 on the right bank of the Tom River 15 km north of the city of Tomsk. The Siberian complex was commissioned in 1953. It is the largest complex for the production of plutonium, uranium and transuranic elements in the Russian Federation. The Siberian complex includes five uranium-graphite production reactors that began operation during 1958-1963, enrichment and fuel fabrication facilities and a reprocessing plant [B7].

84. Radionuclides in liquid wastes are discharged into the Tom River, which flow into the Ob River. An estimate of the collective dose from radioactive discharges of the Siberian complex during the period 1958-1992 is presented in Table 26. The exposure pathways considered in the dose estimates were the ingestion of fish, drinking water, waterfowl and irrigated products and external exposure from

the contaminated floodplain. The collective effective dose was estimated to be 200 man Sv. A major contribution to this dose was due to fish consumption (73%). The main radionuclides contributing to the internal dose from fish consumption were ^{32}P and ^{24}Na. A major portion of the collective dose (about 80%) was received by the population living within 30 km of the site of radioactive discharges.

85. In 1990-1992, three of the five reactors of the Siberian complex were shut down. This reduced considerably the amount of radioactive discharges to the Tom River and the annual collective dose to the population. The average annual doses to the local population are estimated to be 0.4 μSv (external) and 5 μSv (internal). For the local population of 400,000, the collective effective dose at present (1993-1996) is estimated to be 2.2 man Sv (Table 28).

86. On 6 April 1993, an accident occurred at the radiochemical plant of the Siberian complex, resulting in the release of radioactive materials [B7, G6, I6]. A narrow trace of radioactive contamination 35-45 km long was formed in a northeasternly direction from the Siberian complex (based on trace concentrations of ^{95}Zr and ^{95}Nb in soil). The total area of the contamination with dose rate levels at the time of the accident higher than the natural radiation background was estimated to be about 100 km^2 [M8]. The dominant radionuclides in snow samples from the contaminated area were ^{95}Zr, ^{95}Nb, ^{106}Ru and ^{103}Ru. Traces of ^{239}Pu and ^{144}Ce were also detected. A non-uniformity of contamination was noted with the presence of hot particles in the composition of radioactive materials deposited on the snow. There are no populated places in the area of the pattern, except for the village of Georgievka, which has a population of 67 persons (including 18 children). The external dose to inhabitants of Georgievka from the accident over 50 years of permanent residence will amount to 0.2-0.3 mSv [B7], which is negligible, when compared to the dose from natural background radiation over the same period. On the whole, the radiation accident at the Siberian complex did not lead to significant radiological consequences for the population.

3. United Kingdom

87. Production of nuclear materials and fabrication of weapons began in the 1950s in the United Kingdom. The work was carried on for several years at sites such as Springfields (uranium processing and fuel fabrication), Capenhurst (enrichment), Sellafield (production reactors and reprocessing), Aldermaston (weapons fabrication) and Harwell (research). Subsequently, work related to the commercial nuclear power programme was incorporated at some of these sites. The lack of earlier reported data on radionuclide discharges to the environment and the combined operations subsequently may make it difficult to assess the exposures caused by the operation of the military fuel cycle.

88. Plutonium production reactors were operated in the United Kingdom at Sellafield (2 graphite-moderated, gas-cooled reactors known as the Windscale piles) and later at Calder Hall on the Sellafield site and Chapelcross in Scotland. A fire occurred in one of the Windscale reactors in 1957, resulting in the release of radionuclides, most notably ^{131}I, ^{137}Cs, ^{106}Ru, ^{133}Xe and ^{210}Po. A prompt imposition of a ban on milk supplies in the affected region reduced exposures to ^{131}I. The collective effective dose from the accident was estimated to be 2000 man Sv. Further details of the accident were reviewed in the UNSCEAR 1993 Report [U3].

4. France

89. A nuclear programme in France began in 1945 with the creation of the Commissariat à l'Energíe Atomique (CEA). The nuclear research laboratory at Fontenay-aux-Roses began activities in the following year. The first experimental reactor, named EL1 or Zoé, went critical in 1948, and a pilot

reprocessing plant began operation in 1954. A second experimental reactor, EL2, was constructed at the Saclay centre. From 1956 to 1959, three larger production reactors began operation at the Marcoule complex on the Rhône River. These gas-cooled, graphite-moderated reactors, designated G1, G2 and G3, operated until 1968, 1980 and 1984 and provided the basis for design of the first commercial nuclear power reactors in France. A full-scale reprocessing plant, UP1, was built and operated from 1958 also at the Marcoule site. Two further reprocessing plants were constructed at La Hague in the north of France, UP2 completed in 1966 and UP3 in 1990, to process fuel from commercial reactors.

90. Although some systematic reporting of radionuclide discharge data is available beginning in 1972 [C10], some of this may reflect reprocessing of commercial reactor fuel. It should be possible to estimate plutonium production amounts at the various installations, and some reports of environmental monitoring (e.g. [M9]) may give indications of early operating experience.

5. China

91. A nuclear weapons development programme was initiated in China that led to the first nuclear explosion of that country conducted in 1964. The Institute of Atomic Energy was created in 1950. The first experimental reactor was constructed in Beijing, and a uranium enrichment plant was built in Lanzhou in Ganzu Province in western China. The first nuclear test was of an enriched uranium device. Plutonium production and reprocessing were conducted at the Jinquan complex also located in Ganzu Province. The production reactor began operation in 1967 and the reprocessing plant in 1968. Production and reprocessing has also occurred in Guangyuan in Sichun Province, where larger installations were constructed. The weapons were assembled at the Jinquan complex.

92. Assessment of exposures from nuclear weapons production in China should be possible from data provided by Pan et al. [P4, P5, P6]. The release data cannot always be related to specific installations and locations, but estimates of exposures to populations surrounding specific installations have been made. This experience relates to the military fuel cycle, since the commercial nuclear power programme only started within the last decade. As for the other countries producing nuclear weapons, it will be necessary to estimate the enriched uranium and plutonium production amounts or the number of warheads fabricated in order to normalize the results and make comparable exposure estimates.

[Availability of radionuclide release data from installations involved in nuclear weapons production, especially in the earliest periods, will be investigated, and further evaluation of exposures from this practice will be added.]

Table 1
Atmospheric nuclear tests

CHINA

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local*	*Troposphere*	*Stratosphere*
Test site: Lop Nor							
1964: 16 October	Land surface	0.02	0	0.02	0.01	0.01	
1965: 14 May	Air	0.04	0	0.04		0.037	0.003
1966: 9 May	Air	0.3	0	0.3		0.17	0.13
27 October	Air	0.02	0	0.02		0.02	
28 December	Land surface	0.3	0	0.3	0.15	0.085	0.065
1967: 17 January	Air	1.5	1.5	3			1.5
24 December	Air	0.02	0	0.02		0.02	
1968: 28 December	Air	1.5	1.5	3			1.5
1969: 29 September	Air	1.5	1.5	3			1.5
1970: 14 October	Air	1.5	1.5	3			1.5
1971: 18 November	Land surface	0.02	0	0.02	0.01	0.01	
1972: 7 January	Air	0.02	0	0.02		0.02	
18 March	Air	0.1	0	0.1		0.08	0.02
1973: 27 June	Air	1.25	1.25	2.5			1.25
1974: 17 June	Air	0.3	0.3	0.6		0.065	0.235
1976: 23 January	Land surface	0.02	0	0.02	0.01	0.01	
26 September	Air	0.1	0	0.1		0.08	0.02
17 November	Air	2	2	4			2
1977: 17 September	Air	0.02	0	0.02		0.02	
1978: 15 March	Land surface	0.02	0	0.02	0.01	0.01	
14 December	Land surface	0.02	0	0.02	0.01	0.01	
1980: 16 October	Air	0.3	0.3	0.6		0.07	0.24

FRANCE

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local*	*Troposphere*	*Stratosphere*
Test site: Algeria							
1960: 13 February	Tower	0.067 [b]	0	0.067	0.0335	0.0326	0.0009
1 April	Land surface	0.003 [b]	0	0.003	0.0015	0.0015	
27 December	Tower	0.002 [b]	0	0.002	0.001	0.001	
1961: 25 April	Tower	0.0007 [b]	0	0.0007	0.00035	0.00035	
Test site: Fangataufa							
1966: 24 September	Barge	0.125 [b]	0	0.125	0.0625	0.0595	0.003
1968: 24 August	Balloon	1.3	1.3	2.6			1.3
1970: 30 May	Balloon	0.4725	0.4725	0.945			0.4725
3 August	Balloon	0.072	0	0.072		0.07	0.002

Table 1 (continued)

Date	Type of test	Yield (Mt) [a]			Partitioned fission yield (Mt)		
		Fission	Fusion	Total	Local	Troposphere	Stratosphere
Test site: Mururoa							
1966: 2 July	Barge	0.028 [b]	0	0.028	0.014	0.014	
19 July	Air drop	0.05 [b]	0	0.05		0.049	0.001
11 September	Balloon	0.11 [b]	0	0.11			0.11
4 October	Barge	0.205 [b]	0	0.205	0.1025	0.0921	0.0104
1967: 5 June	Balloon	0.015 [b]	0	0.015		0.015	
27 June	Balloon	0.12 [b]	0	0.12			0.12
2 July	Barge	0.022 [b]	0	0.022	0.011	0.011	
1968: 7 July	Balloon	0.115 [b]	0	0.115			0.115
15 July	Balloon	0.45 [b]	0	0.45			0.45
3 August	Balloon	0.15 [b]	0	0.15			0.15
8 September	Balloon	0.64	0.64	1.28			0.64
1970: 15 May	Balloon	0.013 [b]	0	0.013		0.013	
22 May	Balloon	0.224	0	0.224			0.224
24 June	Balloon	0.012 [b]	0	0.012		0.012	
3 July	Balloon	0.457	0.457	0.914			0.457
27 July	Balloon	0.00005 [b]	0	0.00005		0.00005	
6 August	Balloon	0.297	0.297	0.594			0.297
1971: 5 June	Balloon	0.034 [b]	0	0.034		0.034	
12 June	Balloon	0.44	0	0.44			0.44
4 July	Balloon	0.009 [b]	0	0.009		0.009	
8 August	Balloon	0.004 [b]	0	0.004		0.004	
14 August	Balloon	0.478	0.477	0.955			0.478
1972: 25 June	Balloon	0.0005 [b]	0	0.0005		0.0005	
30 June	Balloon	0.004 [b]	0	0.004		0.004	
27 July	Balloon	0.006 [b]	0	0.006		0.006	
1973: 21 July	Balloon	0.011 [b]	0	0.011		0.011	
28 July	Balloon	0.00005 [b]	0	0.00005		0.00005	
18 August	Balloon	0.004 [b]	0	0.004		0.004	
24 August	Balloon	0.0002 [b]	0	0.0002		0.0002	
28 August	Air drop	0.006 [b]	0	0.006		0.006	
1974: 16 June	Balloon	0.004 [b]	0	0.004		0.004	
7 July	Balloon	0.15	0	0.15			0.15
17 July	Balloon	0.004 [b]	0	0.004		0.004	
25 July	Air drop	0.008 [b]	0	0.008		0.008	
15 August	Balloon	0.096	0	0.096		0.093	0.003
24 August	Balloon	0.014 [b]	0	0.014		0.014	
14 September	Balloon	0.332	0	0.332			0.332

UNITED KINGDOM

Date	Type of test	Yield (Mt) [a]			Partitioned fission yield (Mt)		
		Fission	Fusion	Total	Local	Troposphere	Stratosphere
Test site: Monte Bello, Australia							
1952: 3 October	Water surface	0.025	0	0.025	0.0125	0.0125	
1956: 16 May	Tower (31 m)	0.015	0	0.015	0.0075	0.0075	
19 June	Tower (31 m)	0.06	0	0.06	0.03	0.0293	0.0007
Test site: Emu, Australia							
1953: 14 October	Tower (31 m)	0.01	0	0.01	0.005	0.005	
26 October	Tower (31 m)	0.008	0	0.008	0.004	0.004	

Table 1 (continued)

Date	Type of test	Yield (Mt) [a]			Partitioned fission yield (Mt)		
		Fission	Fusion	Total	Local	Troposphere	Stratosphere
Test site: Maralinga, Australia							
1956: 27 September	Tower (31 m)	0.015	0	0.015	0.0075	0.0075	
4 October	Land surface	0.0015	0	0.0015	0.00075	0.00075	
11 October	Air drop (150 m)	0.003	0	0.003		0.003	
22 October	Tower (31 m)	0.01	0	0.01	0.005	0.005	
1957: 14 September	Tower (31 m)	0.001	0	0.001		0.001	
25 September	Tower (31 m)	0.006	0	0.006		0.006	
9 October	Balloon (300 m)	0.025	0	0.025		0.025	
Test site: Malden Island, Pacific							
1957: 15 May	Air burst	0.3	0	0.3		0.26	0.04
31 May	Air burst	0.36	0.36	0.72		0.265	0.095
19 June	Air burst	0.2	0	0.2		0.18	0.02
Test site: Christmas Island, Pacific							
1957: 8 November	Air burst	0.9	0.9	1.8		0.315	0.585
1958: 28 April	Air burst	1.5	1.5	3		0.12	1.38
22 August	Air burst	0.024	0	0.024		0.024	
2 September	Air burst	0.5	0.5	1		0.325	0.175
11 September	Air burst	0.4	0.4	0.8		0.285	0.115
23 September	Air burst	0.025	0	0.025		0.025	

UNITED STATES

Date	Type of test	Yield (Mt) [a]			Partitioned fission yield (Mt)		
		Fission	Fusion	Total	Local	Troposphere	Stratosphere
Test site: New Mexico							
1945: 16 July	Tower	0.021	0	0.021	0.011	0.01	
Hiroshima.Nagasaki, Japan (combat use)							
1945: 5 August	Air drop	0.015	0	0.015		0.015	
9 August	Air drop	0.021	0	0.021		0.021	
Test site: Nevada							
1951: 27 January	Air drop	0.001	0	0.001		0.001	
28 January	Air drop	0.008	0	0.008		0.008	
1 February	Air drop	0.001	0	0.001		0.001	
2 February	Air drop	0.008	0	0.008		0.008	
6 February	Air drop	0.022	0	0.022		0.022	
22 October	Tower	0.0001	0	0.0001	0.00005	0.00005	
28 October	Air drop	0.0035	0	0.0035		0.0035	
30 October	Air drop	0.014	0	0.014		0.014	
1 November	Air drop	0.021	0	0.021		0.021	
5 November	Air drop	0.031	0	0.031		0.031	
19 November	Surface	0.0012	0	0.0012	0.0006	0.0006	
1952: 1 April	Air drop	0.001	0	0.001		0.001	
15 April	Air drop	0.001	0	0.001		0.001	
22 April	Air drop	0.031	0	0.031		0.031	
1 May	Air drop	0.019	0	0.019		0.019	
7 May	Tower	0.012	0	0.012	0.006	0.006	
25 May	Tower	0.011	0	0.011	0.0055	0.0055	
1 June	Tower	0.015	0	0.015	0.0075	0.0075	
5 June	Tower	0.014	0	0.014	0.007	0.007	

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local*	*Troposphere*	*Stratosphere*
1953: 17 March	Tower	0.016	0	0.016	0.008	0.008	
24 March	Tower	0.024	0	0.024	0.012	0.012	
31 March	Tower	0.0002	0	0.0002	0.0001	0.0001	
6 April	Air drop	0.011	0	0.011		0.011	
11 April	Tower	0.0002	0	0.0002	0.0001	0.0001	
18 April	Tower	0.023	0	0.023	0.012	0.011	
25 April	Tower	0.043	0	0.043	0.022	0.021	
8 May	Air drop	0.027	0	0.027		0.027	
19 May	Tower	0.032	0	0.032	0.016	0.016	
25 May	Airburst	0.015	0	0.015		0.015	
4 June	Air drop	0.061	0	0.061		0.0595	0.0015
1955: 18 February	Air drop	0.001	0	0.001		0.001	
22 February	Tower	0.002	0	0.002	0.001	0.001	
1 March	Tower	0.007	0	0.007	0.0035	0.0035	
7 March	Tower	0.043	0	0.043	0.0215	0.0215	
12 March	Tower	0.004	0	0.004	0.002	0.002	
22 March	Tower	0.008	0	0.008	0.004	0.004	
29 March	Tower	0.014	0	0.014	0.007	0.007	
29 March	Air drop	0.003	0	0.003		0.003	
6 April	Air drop	0.003	0	0.003		0.003	
9 April	Tower	0.002	0	0.002	0.001	0.001	
15 April	Tower	0.022	0	0.022	0.011	0.011	
5 May	Tower	0.029	0	0.029	0.0145	0.0145	
15 May	Tower	0.028	0	0.028	0.014	0.014	
1957: 28 May	Tower	0.012	0	0.012	0.006	0.006	
2 June	Tower	0.00014	0	0.00014	0.00007	0.00007	
5 June	Balloon	0.0000005	0	0.0000005		0.0000005	
18 June	Balloon	0.01	0	0.01		0.01	
24 June	Balloon	0.037	0	0.037		0.037	
5 July	Balloon	0.074	0	0.074		0.072	0.002
15 July	Tower	0.017	0	0.017	0.0085	0.0085	
19 July	Rocket	0.002	0	0.002		0.002	
24 July	Tower	0.01	0	0.01	0.005	0.005	
25 July	Balloon	0.0097	0	0.0097		0.0097	
7 August	Balloon	0.019	0	0.019		0.019	
18 August	Tower	0.017	0	0.017	0.0085	0.0085	
23 August	Balloon	0.011	0	0.011		0.011	
30 August	Balloon	0.0047	0	0.0047		0.0047	
31 August	Tower	0.044	0	0.044	0.022	0.022	
2 September	Tower	0.011	0	0.011	0.0055	0.0055	
6 September	Balloon	0.0002	0	0.0002		0.0002	
8 September	Balloon	0.001	0	0.001		0.001	
14 September	Tower	0.011	0	0.011	0.0055	0.0055	
16 September	Balloon	0.012	0	0.012		0.012	
23 September	Tower	0.019	0	0.019	0.0095	0.0095	
28 September	Balloon	0.012	0	0.012		0.012	
7 October	Balloon	0.008	0	0.008		0.008	
1958: 19 September	Balloon	0.000083	0	0.000083		0.000083	
29 September	Balloon	0.002	0	0.002		0.002	
10 October	Tower	0.000079	0	0.000079	0.00004	0.000039	
13 October	Balloon	0.0014	0	0.0014		0.0014	
15 October	Tower	0.0000012	0	0.0000012	0.0000006	0.0000006	
16 October	Balloon	0.000037	0	0.000037		0.000037	
18 October	Tower	0.00009	0	0.00009	0.000045	0.000045	
22 October	Balloon	0.006	0	0.006		0.006	
22 October	Balloon	0.00012	0	0.00012		0.00012	
22 October	Balloon	0.00019	0	0.00019		0.00019	
26 October	Balloon	0.0049	0	0.0049		0.0049	
26 October	Balloon	0.0022	0	0.0022		0.0022	
29 October	Tower	0.0000078	0	0.0000078	0.0000039	0.0000039	
29 October	Tower	0	0	0	0	0	
30 October	Balloon	0.0013	0	0.0013		0.0013	
1962: 7 July	Surface	0.02	0	0.02 [c]	0.01	0.01	
14 July	Tower	0.02	0	0.02 [c]	0.01	0.01	
17 July	Surface	0.02	0	0.02 [c]	0.01	0.01	

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local*	*Troposphere*	*Stratosphere*
Test site: Bikini, Pacific							
1946: 30 June	Air drop	0.021	0	0.021		0.021	
24 July	Under water	0.021	0	0.021	0.011	0.01	
1954: 28 February	Surface	5	10	15	2.5		2.5
26 March	Barge	3.67	7.33	11	1.83		1.83
6 April	Surface	0.11	0	0.11	0.055	0.053	0.002
25 April	Barge	3.45	3.45	6.9	1.725		1.725
4 May	Barge	4.5	9.0	13.5	2.25		2.25
1956: 20 May	Air drop	1.9	1.9	3.8		0.09	1.81
27 May	Surface	1.75	1.75	3.5	0.875	0.053	0.822
11 June	Barge	0.365	0	0.365	0.183	0.154	0.028
25 June	Barge	0.55	0.55	1.1	0.275	0.168	0.107
10 July	Barge	2.25	2.25	4.5	1.125	0.026	1.099
20 July	Barge	2.5	2.5	5	1.25	0.005	1.245
1958: 11 May	Barge	0.68	0.68	1.36	0.34	0.175	0.165
21 May	Barge	0.0251	0	0.0251	0.0126	0.0125	
31 May	Barge	0.092	0	0.092	0.046	0.0446	0.0014
10 June	Barge	0.213	0	0.213	0.107	0.095	0.011
14 June	Barge	0.319	0	0.319	0.16	0.137	0.022
27 June	Barge	0.412	0	0.412	0.206	0.171	0.035
29 June	Barge	0.014	0	0.014	0.007	0.007	
2 July	Barge	0.22	0	0.22	0.11	0.11	
12 July	Barge	4.65	4.65	9.3	2.325		2.325
22 July	Barge	0.065	0	0.065	0.0325	0.0316	0.0009
Test site: Enewetak, Pacific							
1948: 14 April	Tower	0.037	0	0.037	0.019	0.018	
30 April	Tower	0.049	0	0.049	0.025	0.024	
14 May	Tower	0.018	0	0.018	0.009	0.009	
1951: 7 April	Tower	0.081	0	0.081	0.041	0.039	0.001
20 April	Tower	0.047	0	0.047	0.024	0.023	
8 May	Tower	0.225	0	0.225	0.113	0.100	0.012
24 May	Tower	0.0455	0	0.0455	0.0228	0.0227	
1952: 31 October	Surface	3.47	6.93	10.4	1.73		1.74
15 November	Air drop	0.25	0.25	0.5		0.2	0.05
1954: 13 May	Barge	0.845	0.845	1.69	0.423	0.164	0.258
1956: 4 May	Surface	0.04	0	0.04	0.02	0.02	
27 May	Tower	0.00019	0	0.00019	0.000095	0.000095	
30 May	Tower	0.0149	0	0.0149	0.00745	0.00745	
6 June	Surface	0.0137	0	0.0137	0.00685	0.00685	
11 June	Tower	0.008	0	0.008	0.004	0.004	
13 June	Tower	0.00149	0	0.00149	0.000745	0.000745	
16 June	Air drop	0.0017	0	0.0017		0.0017	
21 June	Tower	0.0152	0	0.0152	0.0076	0.0076	
2 July	Tower	0.36	0	0.36	0.18	0.152	0.028
8 July	Barge	0.925	0.925	1.85	0.463	0.153	0.309
21 July	Barge	0.25	0	0.25	0.125	0.110	0.015
1958: 5 May	Surface	0.018	0	0.018	0.009	0.009	
11 May	Barge	0.081	0	0.081	0.041	0.0388	0.0012
12 May	Surface	0.685	0.685	1.37	0.343	0.175	0.167
16 May	Under water	0.009	0	0.009	0.0045	0.0045	
20 May	Barge	0.0059	0	0.0059	0.003	0.0029	
26 May	Barge	0.33	0	0.33	0.165	0.141	0.024
26 May	Barge	0.057	0	0.057	0.0285	0.0278	0.0007
30 May	Barge	0.0116	0	0.0116	0.0058	0.0058	
2 June	Barge	0.015	0	0.015	0.0075	0.0075	
8 June	Under water	0.008	0	0.008	0.004	0.004	
14 June	Barge	0.725	0.725	1.45	0.363	0.174	0.188
18 June	Barge	0.011	0	0.011	0.0055	0.0055	
27 June	Barge	0.44	0.44	0.88	0.22	0.151	0.069
28 June	Barge	4.45	4.45	8.9	2.225		2.225
1 July	Barge	0.0052	0	0.0052	0.0026	0.0026	
5 July	Barge	0.397	0	0.397	0.199	0.165	0.033
17 July	Barge	0.255	0	0.255	0.128	0.112	0.015

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local*	*Troposphere*	*Stratosphere*
1958: 22 July	Barge	0.202	0	0.202	0.101	0.0909	0.0101
26 July	Barge	1	1	2	0.5	0.138	0.363
6 August	Surface	0	0	0	0	0	
18 August	Surface	0.00002	0	0.00002	0.00001	0.00001	
Test site: Pacific							
1955: 14 May	Under water	0.03	0	0.03	0.015	0.015	
1958: 28 April	Balloon	0.0017	0	0.0017		0.0017	
1962: 6 May	Rocket	0.05	0	0.05 [c]			0.05
11 May	Under water	0.02	0	0.02 [c]	0.01	0.01	
Test site: Atlantic, 38°-50°S							
1958: 27 August	Rocket	0.0015	0	0.0015			0.0015
30 August	Rocket	0.0015	0	0.0015			0.0015
6 September	Rocket	0.0015	0	0.0015			0.0015
Test site: Johnston Island, Pacific							
1958: 1 August	Rocket	1.9	1.9	3.8			1.9
12 August	Rocket	1.9	1.9	3.8			1.9
1962: 9 July	Rocket	0.7	0.7	1.4			0.7
2 October	Air drop	0.075	0	0.075		0.073	0.002
6 October	Air drop	0.0113	0	0.0113		0.0113	
18 October	Air drop	0.795	0.795	1.59		0.341	0.454
20 October	Rocket	0.02	0	0.02 [c]			0.02
26 October	Rocket	0.25	0.25	0.5 [c]			0.25
27 October	Air drop	0.4	0.4	0.8		0.285	0.115
30 October	Air drop	4.15	4.15	8.3			4.15
1 November	Rocket	0.25	0.25	0.5 [c]			0.25
4 November	Rocket	0.02	0	0.02 [c]			0.02
Test site: Christmas Island, Pacific							
1962: 25 April	Air drop	0.19	0	0.19		0.172	0.018
27 April	Air drop	0.41	0	0.41		0.340	0.070
2 May	Air drop	0.545	0.545	1.09		0.336	0.209
4 May	Air drop	0.335	0.335	0.67		0.252	0.083
8 May	Air drop	0.1	0	0.1		0.097	0.003
9 May	Air drop	0.1	0	0.1		0.097	0.003
11 May	Air drop	0.05	0	0.05		0.049	0.001
12 May	Air drop	0.25	0.25	0.5		0.2	0.05
14 May	Air drop	0.097	0	0.097		0.094	0.003
19 May	Air drop	0.073	0	0.073		0.071	0.002
25 May	Air drop	0.0026	0	0.0026		0.0026	
27 May	Air drop	0.043	0	0.043		0.043	
8 June	Air drop	0.391	0.391	0.782		0.281	0.110
9 June	Air drop	0.21	0	0.21		0.188	0.022
10 June	Air drop	1.5	1.5	3		0.12	1.38
12 June	Air drop	0.6	0.6	1.2		0.345	0.255
15 June	Air drop	0.4	0.4	0.8		0.28	0.12
17 June	Air drop	0.052	0	0.052		0.051	0.001
19 June	Air drop	0.0022	0	0.0022		0.0022	
22 June	Air drop	0.0815	0	0.0815		0.0791	0.0024
27 June	Air drop	3.83	3.82	7.65			3.83
30 June	Air drop	0.63	0.64	1.27		0.346	0.284
10 July	Air drop	0.5	0.5	1		0.325	0.175
11 July	Air drop	1.94	1.94	3.88		0.089	1.851

Table 1 (continued)

USSR

Date	Type of test	Yield (Mt)[a]			Partitioned fission yield (Mt)		
		Fission	Fusion	Total	Local	Troposphere	Stratosphere
Test site: Semipalatinsk							
1949: 29 August	Surface	0.022	0.022	0.022	0.011	0.011	
1951: 24 September	Surface	0.038	0	0.038	0.019	0.018	0.001
18 October	Air	0.042	0	0.042		0.039	0.003
1953: 12 August	Surface	0.04	0.36	0.4[d]	0.02	0.0089	0.011
23 August	Air	0.028	0	0.028		0.028	
3 September	Air	0.0058	0	0.0058		0.0058	
8 September	Air	0.0016	0	0.0016		0.0016	
10 September	Air	0.0049	0	0.0049		0.0049	
1954: 29 September	Air	0.0002	0	0.0002		0.0002	
1 October	Air	0.00003	0	0.00003		0.00003	
3 October	Air	0.002	0	0.002		0.002	
5 October	Surface	0.004	0	0.004	0.002	0.002	
8 October	Air	0.0008	0	0.0008		0.0008	
19 October	Surface	0.000001	0	0.000001	0.0000005	0.0000005	
23 October	Air	0.062	0	0.062		0.054	0.008
26 October	Air	0.0028	0	0.0028		0.0028	
30 October	Surface	0.01	0	0.01	0.005	0.005	
1955: 29 July	Surface	0.0013	0	0.0013	0.00065	0.00065	
2 August	Surface	0.012	0	0.012	0.006	0.006	
5 August	Surface	0.0012	0	0.0012	0.0006	0.0006	
6 November	Air	0.25	0	0.25		0.158	0.092
22 November	Air	0.8	0.8	1.6		0.003	0.797
1956 16 March	Surface	0.014	0	0.014	0.007	0.007	
25 March	Surface	0.0055	0	0.0055	0.00275	0.00275	
24 August	Surface	0.027	0	0.027	0.0135	0.0135	
30 August	Air	0.45	0.45	0.9		0.020	0.430
2 September	Air	0.051	0	0.051		0.046	0.005
10 September	Air	0.038	0	0.038		0.036	0.002
17 November	Air	0.45	0.45	0.9		0.020	0.430
14 December	Air	0.04	0	0.04		0.037	0.003
1957: 8 March	Air	0.019	0	0.019		0.019	
3 April	Air	0.042	0	0.042		0.039	0.003
6 April	Air	0.057	0	0.057		0.050	0.007
10 April	High atmosphere	0.34	0.34	0.68		0.046	0.294
12 April	Air	0.022	0	0.022		0.022	
16 April	Air	0.32	0	0.32		0.173	0.147
22 August	Air	0.26	0.26	0.52		0.078	0.182
26 August	Air	0.0001	0	0.0001		0.0001	
13 September	Air	0.0059	0	0.0059		0.0059	
26 September	Air	0.013	0	0.013		0.013	
28 December	Air	0.012	0	0.012		0.012	
1958: 4 January	Air	0.0013	0	0.0013		0.0013	
17 January	Air	0.0005	0	0.0005		0.0005	
13 March	Air	0.0012	0	0.0012		0.0012	
14 March	Air	0.035	0	0.035		0.033	0.002
15 March	High atmosphere	0.014	0	0.014		0.014	
18 March	Air	0.00016	0	0.00016		0.00016	
20 March	High atmosphere	0.012	0	0.012		0.012	
22 March	Air	0.018	0	0.018		0.018	
1961: 1 September	Air	0.016	0	0.016		0.016	
4 September	Air	0.009	0	0.009		0.009	
5 September	Air	0.016	0	0.016		0.016	
6 September	Air	0.0011	0	0.0011		0.0011	
9 September	Surface	0.00038	0	0.00038	0.00019	0.00019	
10 September	Air	0.00088	0	0.00088		0.00088	
11 September	Air	0.0003	0	0.0003		0.0003	
13 September	Air	0.004	0	0.004[e]		0.005	
14 September	Surface	0.0004	0	0.0004	0.0002	0.0002	
17 September	Air	0.04	0	0.04[e]		0.045	0.005
18 September	Surface	0.000004	0	0.000004	0.000002	0.000002	
18 September	Air	0.00075	0	0.00075		0.00075	

Table 1 (continued)

Date	Type of test	Yield (Mt)[a]			Partitioned fission yield (Mt)		
		Fission	Fusion	Total	Local	Troposphere	Stratosphere
1961: 19 September	Surface	0.00003	0	0.00003	0.000015	0.000015	
20 September	Air	0.0048	0	0.0048		0.0048	
21 September	Air	0.0008	0	0.0008		0.0008	
26 September	Air	0.0012	0	0.0012		0.0012	
1 October	Air	0.003	0	0.003		0.003	
4 October	Air	0.013	0	0.013		0.013	
12 October	Air	0.015	0	0.015		0.015	
17 October	Air	0.0066	0	0.0066		0.0066	
19 October	Air	0.004	0	0.004 [e]		0.004	
25 October	Air	0.0005	0	0.0005		0.0005	
30 October	Air	0.00009	0	0.00009		0.00009	
1 November	Air	0.0027	0	0.0027		0.0027	
2 November	Air	0.0006	0	0.0006		0.0006	
3 November	Surface	0.000001	0	0.000001	0.0000005	0.0000005	
3 November	Air	0.0009	0	0.0009		0.0009	
4 November	Surface	0.0002	0	0.0002	0.0001	0.0001	
1962: 1 August	Air	0.0024	0	0.0024		0.0024	
3 August	Air	0.0016	0	0.0016		0.0016	
4 August	Air	0.0038	0	0.0038		0.0038	
7 August	Surface	0.0099	0	0.0099	0.00495	0.00495	
18 August	Air	0.0074	0	0.0074		0.0074	
18 August	Air	0.0058	0	0.0058		0.0058	
21 August	Air	0.04	0	0.04 [e]		0.037	0.003
22 August	Air	0.003	0	0.003		0.003	
23 August	Air	0.0025	0	0.0025		0.0025	
25 August	Air	0.004	0	0.004 [e]		0.004	
27 August	Air	0.011	0	0.011		0.011	
31 August	Air	0.0027	0	0.0027		0.0027	
22 September	Surface	0.00021	0	0.00021	0.00011	0.0001	
24 September	Air	0.0012	0	0.0012		0.0012	
25 September	Surface	0.007	0	0.007	0.0035	0.0035	
28 September	Air	0.0013	0	0.0013		0.0013	
9 October	Air	0.008	0	0.008		0.008	
10 October	Air	0.0092	0	0.0092		0.0092	
13 October	Air	0.0049	0	0.0049		0.0049	
14 October	Air	0.004	0	0.004 [e]		0.004	
20 October	Air	0.0067	0	0.0067		0.0067	
28 October	Air	0.0078	0	0.0078		0.0078	
28 October	Air	0.0078	0	0.0078		0.0078	
30 October	Surface	0.0012	0	0.0012	0.0006	0.0006	
31 October	Air	0.01	0	0.01		0.01	
1 November	Air	0.003	0	0.003		0.003	
3 November	Air	0.0047	0	0.0047		0.0047	
4 November	Air	0.0084	0	0.0084		0.0084	
5 November	Surface	0.0004	0	0.0004	0.0002	0.0002	
11 November	Surface	0.0001	0	0.0001	0.00005	0.00005	
13 November	Surface	0.000001	0	0.000001	0.0000005	0.0000005	
14 November	Air	0.012	0	0.012		0.012	
17 November	Air	0.018	0	0.018		0.018	
24 November	Surface	0.000001	0	0.000001	0.0000005	0.0000005	
26 November	Surface	0.000031	0	0.000031	0.000016	0.000015	
1 December	Air	0.0024	0	0.0024		0.0024	
23 December	Surface	0.000001	0	0.000001	0.0000005	0.0000005	
24 December	Surface	0.000007	0	0.000007	0.00000035	0.00000035	
24 December	Surface	0.000028	0	0.000028	0.000014	0.000014	
Test site: Novaya Zemlya							
1955: 21 September	Under water	0.0035	0	0.0035	0.00175	0.00175	
1957: 7 September	Surface	0.032	0	0.032	0.016	0.0154	0.0006
24 September	Air	0.8	0.8	1.6		0.003	0.797
6 October	Air	1.45	1.45	2.9			1.45
10 October	Under water	0.01	0	0.01	0.005	0.005	
1958: 23 February	Air	0.43	0.43	0.86		0.025	0.405
27 February	Air	0.25	0	0.25		0.158	0.092
27 February	Air	0.75	0.75	1.5		0.004	0.746
14 March	Air	0.04	0	0.04		0.037	0.003

Table 1 (continued)

Date	Type of test	Yield (Mt)[a]			Partitioned fission yield (Mt)		
		Fission	Fusion	Total	Local	Troposphere	Stratosphere
1958: 21 March	Air	0.325	0.325	0.65		0.054	0.271
30 September	Air	0.6	0.6	1.2		0.005	0.595
30 September	Air	0.45	0.45	0.9		0.020	0.430
2 October	Air	0.29	0	0.29		0.168	0.122
2 October	Air	0.04	0	0.04		0.037	0.003
4 October	Air	0.009	0	0.009		0.009	
5 October	Air	0.015	0	0.015		0.015	
6 October	Air	0.0055	0	0.0055		0.0055	
10 October	Air	0.068	0	0.068		0.059	0.009
12 October	Air	0.725	0.725	1.45		0.004	0.721
15 October	Air	0.75	0.75	1.5		0.004	0.746
18 October	Air	1.45	1.45	2.9			1.45
19 October	Air	0.04	0	0.04		0.037	0.003
19 October	Air	0.000001	0	0.000001		0.000001	
20 October	Air	0.44	0	0.44		0.173	0.267
21 October	Air	0.002	0	0.002		0.002	
22 October	Air	1.4	1.4	2.8			1.4
24 October	Air	0.5	0.5	1		0.005	0.495
25 October	Air	0.19	0	0.19		0.135	0.055
25 October	Air	0.0001	0	0.0001		0.0001	
1961: 10 September	Air	1.35	1.35	2.7			1.35
10 September	Air	0.012	0	0.012		0.012	
12 September	Air	0.575	0.575	1.15		0.005	0.570
13 September	Air	0.006	0	0.006		0.006	
14 September	Air	0.6	0.6	1.2		0.005	0.595
16 September	Air	0.415	0.415	0.83		0.029	0.386
18 September	Air	0.5	0.5	1		0.005	0.495
20 September	Air	0.4	0	0.4[c]		0.177	0.223
22 September	Air	0.26	0	0.26		0.161	0.099
2 October	Air	0.25	0	0.25		0.158	0.092
4 October	Air	2	2	4[c]			2
6 October	Air	2	2	4			2
8 October	Air	0.015	0	0.015		0.015	
20 October	Air	0.725	0.725	1.45		0.004	0.721
23 October	Under water	0.0048	0	0.0048	0.0024	0.0024	
23 October	Air	4.17	8.33	12.5			4.17
25 October	Air	0.3	0	0.3		0.17	0.13
27 October	Water surface	0.016	0	0.016	0.008	0.008	
30 October	Air	1.5[b]	48.5[b]	50			1.5
31 October	Air	2.5	2.5	5			2.5
31 October	Air	0.4	0	0.4[c]		0.177	0.223
2 November	Air	0.12	0	0.12		0.094	0.026
2 November	Air	0.28	0	0.28		0.166	0.114
4 November	Air	0.015	0	0.015		0.015	
4 November	Air	0.4	0	0.4[c]		0.177	0.223
4 November	Air	0.006	0	0.006		0.006	
1962: 5 August	Air	7.03	14.07	21.1			7.03
10 August	Air	0.4	0	0.4[c]		0.177	0.223
20 August	Air	1.4	1.4	2.8			1.4
22 August	Air	0.8	0.8	1.6		0.003	0.797
22 August	Water surface	0.006	0	0.006	0.003	0.003	
25 August	Air	2	2	4[c]			2
27 August	Air	2.1	2.1	4.2			2.1
2 September	Air	0.08	0	0.08		0.067	0.013
8 September	Air	0.95	0.95	1.9		0.001	0.949
15 September	Air	1.55	1.55	3.1			1.55
16 September	Air	1.625	1.625	3.25			1.625
18 September	Air	0.675	0.675	1.35		0.004	0.671
19 September	Air	2	2	4[c]			2
21 September	Air	1.2	1.2	2.4			1.2
25 September	Air	6.37	12.73	19.1			6.37
27 September	Air	8.07	16.13	24.2[c]			8.07
7 October	Air	0.32	0	0.32		0.173	0.147
9 October	Air	0.015	0	0.015		0.015	
22 October	Air	4.1	4.1	8.2			4.1
27 October	Air	0.26	0	0.26		0.161	0.099
29 October	Air	0.36	0	0.36		0.177	0.183

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)*[a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local*	*Troposphere*	*Stratosphere*
1962: 30 October	Air	0.28	0	0.28		0.166	0.114
1 November	Air	0.24	0	0.24		0.155	0.085
3 November	Air	0.39	0	0.39		0.178	0.212
3 November	Air	0.045	0	0.045		0.041	0.004
18 December	Air	0.11	0	0.11		0.087	0.023
18 December	Air	0.069	0	0.069		0.059	0.010
20 December	Air	0.0083	0	0.0083		0.0083	
22 December	Air	0.0063	0	0.0063		0.0063	
23 December	Air	0.43	0	0.43		0.175	0.255
23 December	Air	0.0083	0	0.0083		0.0083	
23 December	Air	0.0024	0	0.0024		0.0024	
24 December	Air	0.55	0.55	1.1		0.005	0.545
24 December	Air	8.07	16.13	24.2			8.07
25 December	Air	1.55	1.55	3.1			1.55
25 December	Air	0.0085	0	0.0085		0.0085	
Test site: Totsk, Aralsk							
1954: 14 September	Air	0.04	0	0.04		0.037	0.003
1956: 2 February	Surface	0.0003	0	0.0003	0.00015	0.00015	
Test site: Kapustin Yar							
1957: 19 January	Air	0.01	0	0.01		0.01	
1958: 1 November	Air	0.01	0	0.01		0.01	
3 November	Air	0.01	0	0.01		0.01	
1961: 6 September	Air	0.011	0	0.011		0.011	
6 October	Air	0.04	0	0.04		0.037	0.003
27 October	High atmosphere	0.0012	0	0.0012			0.0012
27 October	High atmosphere	0.0012	0	0.0012			0.0012
1962: 22 October	High atmosphere	0.3	0	0.3			0.30
28 October	High atmosphere	0.3	0	0.3			0.30
1 November	High atmosphere	0.3	0	0.3			0.30

a Estimated fission and fusion yields unless otherwise indicated; reported total yields.
b Reported fission or fusion yield.
c Indefinite reported yield; value assigned as follows: low: 0.02 Mt, no indication: 0.05 Mt, sub Mt: 0.5 Mt.
d Thermonuclear explosion; fission yield estimated [G7].
e Indefinite reported yield; value assigned as follows: 0.000001-0.02 Mt: 0.004 Mt, 0.02-0.15 Mt: 0.04 Mt, 0.15-1.5 Mt: 0.4 Mt, 1.5-10 Mt: 4 Mt, >10 Mt: 24.2 Mt.

Table 2
Atmospheric nuclear tests at each test site

Test site	*Number of tests*	*Yield (Mt)*			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local*	*Troposphere*	*Stratosphere*
China							
Lop Nor	22	10.87	9.85	20.72	0.20	0.71	9.96
France							
Algeria	4	0.073	0	0.073	0.036	0.035	0.001
Fangataufa	4	1.97	1.77	3.74	0.06	0.13	1.78
Mururoa	37	4.51	1.87	6.38	0.13	0.41	3.98
Total	45	6.55	3.64	10.20	0.23	0.57	5.76
United Kingdom							
Monte Bello Island	3	0.1	0	0.1	0.050	0.049	0.0007
Emu	2	0.018	0	0.018	0.009	0.009	0
Marilinga	7	0.062	0	0.062	0.013	0.048	0
Malden Island	3	0.86	0.36	1.22	0	0.71	0.15
Christmas Island	6	3.35	3.30	6.65	0	1.09	2.26
Total	21	4.39	3.66	8.05	0.07	1.91	2.41
United States							
New Mexico	1	0.021	0	0.021	0.011	0.010	0
Japan	2	0.036	0	0.036	0	0.036	0
Nevada	84	1.05	0	1.05	0.28	0.77	0.004
Bikini	23	32.8	44.1	76.8	15.4	1.37	16.0
Enewetak	42	15.4	16.3	31.7	7.58	2.32	5.51
Pacific	4	0.102	0	0.102	0.025	0.027	0.050
Atlantic	3	0.0045	0	0.0045	0	0	0.005
Johnston Island	12	10.5	10.3	20.8	0	0.71	9.76
Christmas Island	24	12.3	10.9	23.3	0	3.86	8.47
Total	195	72.2	81.6	153.8	23.3	9.11	39.8
USSR							
Semipalatinsk	116	3.93	2.66	6.59	0.097	1.34	2.49
Novaya Zemlya	91	83.0	156.7	239.6	0.036	4.06	78.9
Totsk, Aralsk	2	0.040	0	0.040	0	0.037	0.003
Kapustin Yar	10	0.98	0	0.98	0	0.078	0.91
Total	219	87.9	159.3	247.3	0.13	5.51	82.3
All countries							
Total	541 [a]	182	258	440	24	18	140

a Includes 22 safety tests of the United States, 12 safety tests of the United Kingdom and 5 safety tests of France.

Table 3
Estimated fission and fusion yields of atmospheric nuclear tests of total yields equal to or greater than 4 Mt

Date	*Designation*	*Type of test*	*Test site*	*Yield (Mt)*		
				Fission	*Fusion*	*Total*
China						
17 November 1976		Air	Lop Nor	2	2	4
United States						
28 February 1954	Bravo	Surface	Bikini	5.0	10	15
4 May 1954	Yankee	Barge	Bikini	4.5	9.0	13.5
26 March 1954	Romeo	Barge	Bikini	3.67	7.33	11
31 October 1952	Mike	Surface	Enewetak	3.47	6.93	10.4
12 July 1958	Poplar	Barge	Bikini	4.65	4.65	9.3
28 June 1958	Oak	Barge	Enewetak	4.45	4.45	8.9
30 October 1962	Housatonic	Air drop	Johnston Island	4.15	4.15	8.3
27 June 1962	Bighorn	Air drop	Christmas Island	3.83	3.82	7.65
25 April 1954	Union	Barge	Bikini	3.45	3.45	6.9
20 July 1956	Tewa	Barge	Bikini	2.5	2.5	5
10 July 1956	Navaho	Barge	Bikini	2.25	2.25	4.5
USSR						
30 October 1961	Test 130	Air	Novaya Zemlya	1.5	48.5	50
24 December 1962	Test 219	Air	Novaya Zemlya	8.07	16.13	24.2
5 August 1962	Test 147	Air	Novaya Zemlya	7.03	14.07	21.1
25 September 1962	Test 173	Air	Novaya Zemlya	6.37	12.73	19.1
27 September 1962	Test 174	Air	Novaya Zemlya	8.07	16.13	24.2 [a]
23 October 1961	Test 123	Air	Novaya Zemlya	4.17	8.33	12.5
22 October 1962	Test 183	Air	Novaya Zemlya	4.1	4.1	8.2
31 October 1961	Test 131	Air	Novaya Zemlya	2.5	2.5	5
27 August 1962	Test 160	Air	Novaya Zemlya	2.1	2.1	4.2
4 October 1961	Test 113	Air	Novaya Zemlya	2	2	4 [b]
6 October 1961	Test 114	Air	Novaya Zemlya	2.0	2.0	4.0
25 August 1962	Test 158	Air	Novaya Zemlya	2	2	4 [b]
19 September 1962	Test 168	Air	Novaya Zemlya	2	2	4 [b]
Total						
		25 tests		96	193	289

a Reported yield: >10 Mt.
b Reported yield: 1.5-10 Mt.

Table 4
Annual values of fission and fusion yields of nuclear tests and atmospheric partitioning

Year	Number of tests	Yield (Mt)			Partitioned fission yield (Mt)		
		Fission	Fusion	Total	Local	Troposphere	Stratosphere
1945	3	0.057	0	0.057	0.011	0.046	0
1946	2	0.042	0	0.042	0.011	0.031	0
1947							
1948	3	0.10	0	0.10	0.053	0.051	0
1949	1	0.022	0	0.022	0.011	0.011	0
1950							
1951	17	0.59	0	0.59	0.22	0.35	0.018
1952	11	3.85	7.18	11.0	1.77	0.29	1.79
1953	18	0.35	0.36	0.71	1.099	0.24	0.013
1954	16	17.7	30.6	48.3	8.79	0.32	8.59
1955	20	1.26	0.80	2.06	0.10	0.27	0.89
1956	32	12.1	10.8	22.9	4.60	1.20	6.33
1957	46	5.53	4.11	9.64	0.092	1.81	3.62
1958	91	30.5	26.2	56.8	7.70	3.90	18.9
1959							
1960	3	0.072	0	0.072	0.036	0.035	0.0009
1961	59	19.0	67.5	86.52	0.011	1.58	17.43
1962	117	73.3	97.0	170.4	0.052	6.50	66.78
1963							
1964	1	0.02	0	0.02	0.010	0.010	0
1965	1	0.04	0	0.04	0	0.037	0.003
1966	8	1.14	0	1.14	0.33	0.49	0.32
1967	5	1.68	1.50	3.18	0.011	0.046	1.62
1968	6	4.16	3.44	7.60	0	0	4.16
1969	1	1.5	1.5	3	0		1.50
1970	9	3.05	2.73	5.77	0	0.095	2.95
1971	6	0.98	0.48	1.46	0.01	0.057	0.92
1972	5	0.13	0	0.13	0	0.11	0.020
1973	6	1.27	1.25	2.52	0	0.021	1.25
1974	8	0.91	0.3	1.21	0	0.19	0.72
1975							
1976	3	2.12	2	4.12	0.010	0.090	2.02
1977	1	0.02	0	0.02	0	0.020	0
1978	2	0.04	0	0.04	0.020	0.020	0
1979							
1980	1	0.3	0.3	0.6	0	0.065	0.24
TOTAL							
Total	541[a]	182	258	440	24	18	140
Total worldwide dispersion (troposphere and stratosphere)						158	
Total measured in global deposition						155	

a Includes 39 safety tests: 22 by the United States, 12 by the United Kingdom and 5 by France.

Table 5
Partitioning of yields from atmospheric tests into the troposphere and stratospheric regions
[P1]

Total yield (Mt)	*Partitioned yield (Mt)*					
	Equatorial airburst[a] (0 °-30 ° latitude)			*Polar airburst[b] (30 °-90 ° latitude)*		
	Troposphere	*Lower stratosphere*	*Upper stratosphere*	*Troposphere*	*Lower stratosphere*	*Upper stratosphere*
0.03	0.03	0		0.029	0.001	
0.05	0.049	0.001		0.045	0.005	
0.07	0.068	0.002		0.06	0.01	
0.1	0.097	0.003		0.08	0.02	
0.2	0.18	0.02		0.14	0.06	
0.3	0.26	0.04		0.17	0.13	
0.5	0.40	0.10		0.16	0.34	
0.7	0.52	0.18		0.08	0.62	
1	0.65	0.35		0.01	0.99	
2	0.55	1.45			1.6	0.4
3	0.24	2.76			1.45	1.55
5	0.02	4.43	0.55		0.95	4.05
7		4.97	2.03		0.56	6.44
10		5.25	4.75		0.06	9.94
20		3.00	17.0			20
30		2.1	27.9			30
50		0.5	49.5			50

a Atmospheric heights: Troposphere < 17 km, Lower stratosphere 17-24 km, Upper stratosphere 24-50 km.
b Atmospheric heights: Troposphere < 9 km, Lower stratosphere 9-17 km, Upper stratosphere 17-50 km

Table 6
Annual injections of nuclear debris into atmospheric regions

Year	*Fission energy (Mt)*										
	High equatorial atmosphere		*Polar stratosphere North*		*Equatorial stratosphere North*		*Equatorial stratosphere South*		*Troposphere*		*Total*
	North	*South*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*North*	*South*	
1945									0.046		0.046
1946									0.031		0.031
1947											
1948									0.051		0.051
1949									0.011		0.011
1950											
1951				0.0042		0.013			0.35		0.37
1952					0.84	0.95			0.28	0.013	2.08
1953				0.011		0.0015			0.23	0.0090	0.25
1954				0.010	4.28	4.29			0.32		8.91
1955				0.89					0.27		1.16
1956				0.87	0.34	5.12		0.0007	1.15	0.053	7.53
1957	0.34		0.80	1.79		0.29		0.45	0.87	0.89	5.44
1958	1.93	1.90	1.58	6.24	1.91	4.58		0.84	3.48	0.39	22.84
1959											
1960						0.0009			0.035		0.036
1961	0.002		11.0	6.42					1.58		19.00
1962	1.57	0.62	41.4	9.96	1.96	6.99	0.68	3.55	4.56	1.93	73.27
1963											
1964									0.010		0.010
1965				0.0030					0.037		0.040
1966				0.20				0.12	0.28	0.21	0.81
1967					0.78	0.72		0.12	0.020	0.026	1.67
1968			0.78	0.72			1.09	1.56			4.16
1969			0.78	0.72							1.50
1970			0.78	0.72				1.45		0.095	3.05
1971								0.92	0.010	0.047	0.97
1972				0.02					0.10	0.011	0.13
1973					0.45	0.80				0.021	1.27
1974						0.24		0.48	0.065	0.12	0.91
1975											
1976			1.33	0.69					0.090		2.11
1977									0.020		0.02
1978									0.020		0.02
1979											
1980				0.24						0.065	0.3
Total North	3.84		58.47	29.51	10.55	24.01			13.92		140.30
South		2.52					1.77	9.50		3.89	17.69
Global	6.36		133.8						17.81		158.0

Table 7
Annual values of ^{90}Sr in air and deposition

Year	*Concentration in surface air of mid-latitudes (Bq m^{-3})*				*Total hemispheric deposition (PBq)*			
	Northern hemisphere		*Southern hemisphere*		*Northern hemisphere*		*Southern hemisphere*	
	Calculated	*Measured*[a]	*Calculated*	*Measured*[b]	*Calculated*	*Measured*	*Calculated*	*Measured*
1945	0.000035		0	0	0.17		0	
1946	0.000025		0	0	0.13		0	
1947	0.00000025		0	0	0.0025		0	
1948	0.00004		0	0	0.20		0	
1949	0.0000084		0	0	0.041		0	
1950	0.00000026		0	0	0.0026		0	
1951	0.00026		0.00000092	0	1.20		0.0041	
1952	0.00023		0.000010	0	0.94		0.041	
1953	0.00069		0.000086	0	3.60		0.38	
1954	0.0017		0.00046	0	7.99		2.07	
1955	0.0023		0.00050	0	11.3		2.49	
1956	0.0031		0.0007	0	15.0		3.47	
1957	0.0034	0.0019	0.0013	0.000089	17.0		6.14	
1958	0.0063	0.0057	0.0013	0.0013	30.1	23.3	6.54	9.45
1959	0.0057	0.0087	0.0010	0.00089	29.8	38.9	5.18	6.84
1960	0.0024	0.0018	0.00075	0.00067	12.6	9.69	3.91	6.22
1961	0.0026	0.0020	0.00053	0.00090	11.4	13.0	2.80	6.44
1962	0.011	0.012	0.0031	0.0014	53.0	53.4	14.4	9.75
1963	0.023	0.026	0.0023	0.0019	114	97.0	11.6	11.4
1964	0.014	0.015	0.0018	0.0022	73.3	61.3	9.39	15.6
1965	0.0066	0.0054	0.0012	0.0019	34.4	28.6	6.58	13.2
1966	0.0031	0.0023	0.00094	0.0010	15.7	12.1	4.85	7.66
1967	0.0014	0.00090	0.00060	0.00060	7.32	6.24	3.16	4.07
1968	0.00095	0.0012	0.00066	0.00055	4.87	7.22	2.91	3.76
1969	0.0013	0.0008	0.00084	0.0011	6.12	5.45	4.37	5.21
1970	0.0013	0.0014	0.00092	0.00080	6.27	7.62	4.41	4.74
1971	0.0012	0.0013	0.00086	0.00094	6.31	6.97	4.40	5.56
1972	0.00075	0.00043	0.00052	0.00063	3.83	3.19	2.93	3.55
1973	0.00037	0.00021	0.00030	0.00029	1.83	1.18	1.62	1.13
1974	0.00052	0.00067	0.00035	0.00022	2.64	4.46	1.65	1.45
1975	0.00033	0.00038	0.00024	0.00023	1.70	2.16	1.30	1.27
1976	0.00023	0.00013	0.00011	0.000081	1.09	1.00	0.62	0.77
1977	0.00076	0.00038	0.000060	0.000040	3.74	3.01	0.32	0.81
1978	0.00046	0.00043	0.000043	0.000027	2.36	3.70	0.22	0.67
1979	0.00021	0.00013	0.000030	0.000023	1.09	1.12	0.16	0.39
1980	0.00014	0.000091	0.000018	0.000036	0.65	1.11	0.096	0.39
1981	0.00016	0.00023	0.000012	0.000026	0.84	1.65	0.064	0.29
1982	0.000041	0.000057	0.0000080	0.000025	0.22	0.47	0.042	0.22
1983	0.000041	0.000013	0.0000045	0.000094	0.071	0.33	0.024	0.19
1984	0.0000049		0.0000022		0.026	0.27	0.012	0.11
1985	0.0000019		0.0000011		0.0098	0.078	0.0058	0.052
1986	0.00000078		0.00000049		0.0040		0.0027	
1987	0.00000035		0.00000024		0.0018		0.0013	
1988	0.00000017		0.00000011		0.00088		0.00067	
1989	0.000000093		0.000000067		0.00047		0.00036	
1990	0.000000054		0.000000039		0.00028		0.00021	
1991	0.000000034		0.000000024		0.00017		0.00013	
1992	0.000000022		0.000000016		0.00011		0.000082	
1993	0.000000015		0.000000010		0.000075		0.000054	
1994	0.000000010		0.0000000069		0.000051		0.000037	
1995	0.0000000068		0.000000047		0.000035		0.000025	
1996	0.0000000047		0.000000032		0.000024		0.000017	
1997	0.0000000032		0.000000022		0.000016		0.000012	
1998	0.0000000022		0.0000000015		0.000011		0.0000081	
1999	0.0000000015		0.0000000011		0.0000078		0.0000056	
Total[c]	0.098 Bq a m^{-3}		0.019 Bq a m^{-3}		452 PBq 460 PBq[d]		136 PBq 144 PBq[d]	

a Average of measurements performed monthly at Washington, D.C. and Miami (1957-1962), at New York City, Miami and Sterling, Virginia (1963-1973), and at New York City and Miami (1974-1983) [L6, F4].

b Average of measurements performed monthly at Antofagasta and Santiago, Chile (1958-1976) and at Lima, Peru and Santiago, Chile (1977-1983) [L6, F4].

c Measured values included preferentially in total.

d Previously derived value based on measured cumulative deposition prior to 1958 [U6].

Table 8
Cumulative deposition of radionuclides produced in atmospheric nuclear testing calculated from fission yields and empirical atmospheric model

Year	*Cumulative deposition at end of year (PBq)*								
	^{90}Sr			^{137}Cs			^{95}Zr		
	Northern hemisphere	*Southern hemisphere*	*Global*	*Northern hemisphere*	*Southern hemisphere*	*Global*	*Northern hemisphere*	*Southern hemisphere*	*Global*
1945	0.17	0	0.17	0.25	0	0.25	7.24	0	7.24
1946	0.29	0	0.29	0.44	0	0.44	3.29	0	3.29
1947	0.29	0	0.29	0.43	0	0.43	0.065	0	0.65
1948	0.47	0	0.47	0.72	0	0.72	2.58	0	2.58
1949	0.50	0	0.50	0.76	0	0.76	1.88	0	1.88
1950	0.49	0	0.49	0.75	0	0.75	0.039	0	0.039
1951	1.67	0.0040	1.68	2.53	0.0061	2.54	43.1	0.068	43.1
1952	2.56	0.045	2.61	3.88	0.067	3.95	58.2	3.22	61.4
1953	6.06	0.42	6.48	9.17	0.64	9.81	27.2	3.01	30.2
1954	13.8	2.47	16.3	20.9	3.73	24.7	92.9	19.1	112
1955	24.7	4.88	29.6	37.4	7.38	44.8	49.3	0.87	50.1
1956	39.0	8.21	47.2	59.1	12.4	71.5	194	40.0	234
1957	54.9	14.1	69.0	83.2	21.3	105	154	101	255
1958	83.4	20.2	104	126	30.7	157	589	123	712
1959	111	24.9	136	168	37.7	206	40.9	4.71	45.6
1960	121	28.2	149	183	42.7	226	1.89	0.14	2.03
1961	129	30.3	159	196	45.9	242	458	0.0035	458
1962	179	43.8	222	271	66.5	338	992	270	1263
1963	287	54.2	342	436	82.3	518	164	12.6	176
1964	353	62.2	415	536	94.5	630	7.79	0.41	8.20
1965	379	67.2	446	575	102	677	2.70	0.012	2.71
1966	385	70.4	456	585	107	693	20.1	47.5	67.6
1967	383	71.9	455	583	109	693	8.47	13.3	21.8
1968	379	73.1	452	577	111	689	1.42	43.5	44.9
1969	376	75.6	452	573	115	689	22.2	3.94	26.1
1970	373	78.2	451	570	119	689	11.1	46.6	57.7
1971	370	80.7	451	566	123	689	7.77	30.2	38.0
1972	365	81.7	447	559	125	684	3.97	2.64	6.61
1973	359	81.3	440	549	124	673	6.43	9.91	16.3
1974	353	81.0	434	540	124	665	8.48	34.3	42.8
1975	346	80.4	426	531	123	654	0.53	1.46	1.99
1976	339	79.1	418	520	121	642	17.8	0.035	17.9
1977	334	77.5	412	514	119	633	12.6	0.13	12.7
1978	329	75.9	405	506	117	623	0.70	0.0076	0.71
1979	322	74.3	396	496	114	610	0.14	0.00024	0.14
1980	315	72.6	388	486	112	598	19.0	0.000006	19.0
1981	308	70.9	379	476	109	585	1.51	0.021	1.53
1982	301	69.3	371	465	107	572	0.034	0.00093	0.035
1983	294	67.7	362	455	105	560	0.00068	0.00003	0.00071
1984	2 87	66.1	353	445	102	547	0.00001	0.000001	0.00001
1985	280	64.5	345	435	99.9	534			
1986	274	63.0	337	425	97.6	522			
1987	267	61.5	329	415	95.4	510			
1988	261	60.0	321	406	93.2	499			
1989	255	58.6	313	396	91.1	488			
1990	249	57.2	306	387	89.0	476			
1991	243	55.8	298	379	87.0	466			
1992	237	54.5	291	370	85.0	455			
1993	231	53.2	284	362	83.1	445			
1994	226	51.9	278	353	81.2	435			
1995	220	50.7	271	345	79.4	425			
1996	215	49.5	265	337	77.6	415			
1997	210	48.3	258	330	75.8	406			
1998	205	47.2	252	322	74.1	396			
1999	200	46.0	246	315	72.4	387			
2000	195	44.9	240	308	70.7	379			

Table 9
Latitudinal distribution of ^{90}Sr and ^{95}Zr deposition from atmospheric nuclear testing

Latitude band (degrees)	*Area of band* (10^{12} m^2)	*Population distribution* (%)	*Integrated deposition (PBq)*	*Integrated deposition density* [a] ($Bq\ m^{-2}$)	
			^{90}Sr	^{90}Sr	^{95}Zr
Northern hemisphere					
80-90	3.9	0	1.0	260	4800
70-80	11.6	0	7.9	680	12800
60-70	18.9	0.4	32.9	1740	32800
50-60	25.6	13.7	7.3.9	2890	54400
40-50	31.5	15.5	101.6	3230	60800
30-40	36.4	20.4	85.3	2340	44200
20-30	40.2	32.7	71.2	1770	33400
10-20	42.8	11.0	50.9	1190	22400
0-10	44.1	6.3	35.7	810	15300
Total	255	100	460	2140 [b]	40400 [b]
Southern hemisphere					
0-10	44.1	54.0	21.0	480	7400
10-20	42.8	16.7	17.8	420	6500
20-30	40.8	14.9	28.1	700	10900
30-40	36.4	13.0	27.6	760	11800
40-50	31.5	0.9	28.1	890	13900
50-60	25.6	0.5	12.1	470	7400
60-70	18.9	0	6.7	350	5500
70-80	11.6	0	2.5	220	3400
80-90	3.9	0	0.3	80	1200
Total	255	100	144	540 [b]	8400 [b]
Global	510	89 (northern) 11 (southern)	604	1960 [b]	37000 [b]

a Results of global measurements of ^{90}Sr and of calculation with production amounts and atmospheric model for ^{95}Zr.
b Population-weighted values.

Table 10
Global population-weighted average deposition density of ^{90}Sr
[U6]

Year	*Deposition density* [a] ($Bq\ m^{-2}$)	*Year*	*Deposition density* [a] ($Bq\ m^{-2}$)	*Year*	*Deposition density* [a] ($Bq\ m^{-2}$)
1951	0.062	1964	249.5	1977	12.3
1952	8.9	1965	135.6	1978	14.3
1953	12.2	1966	64.3	1979	5.2
1954	60.6	1967	33.4	1980	4.9
1955	58.7	1968	35.7	1981	4.2
1956	74.4	1969	34.4	1982	1.2
1957	77.1	1970	39.9	1983	0.32
1958	106.4	1971	40.9	1984	0.10
1959	148.3	1972	21.7	1985	0.032
1960	51.6	1973	7.5		
1961	63.0	1974	19.1		
1962	205.1	1975	11.4		
1963	351.8	1976	5.8	Total	1960

a The total ^{90}Sr deposition from all atmospheric tests of 604 PBq resulted in the global average integrated deposition density of 1960 Bq m^{-2}. Annual average deposition densities have thus been derived from annual global deposition [U6] times 1960/604. Annual values were not measured in the years 1951-1957 and were therefore estimated from the cumulative ^{90}Sr deposit and the annual fission yields.

Table 11
Parameters for calculation of annual effective doses from external irradiation by longer-lived radionuclides in fallout from atmospheric nuclear testing [a]

Radionuclide	*Half-life*	*Ratio to ^{90}Sr deposition*	*Absorbed dose rate in air per unit deposition density [b] (nGy a^{-1} per Bq m^{-2})*	*Initial effective dose rate per unit deposition density [c] (nSv a^{-1} per Bq m^{-2})*
Mn-54	312.5 d	2.9	31.9	8.04
Ru-106	371.6 d	7.5	7.88 [d]	1.99
Sb-125	2.73 a	0.89	16.3	4.10
Cs-137	30.14 a	1.5	8.89	2.24
Ce-144	284.9 d	15	1.65 [e]	0.42

a The annual dose in a specific year is the deposition density of the radionuclide in that year times $D_0 (1 - e^{-\lambda}) / \lambda$ plus the total external dose in the previous year resulting from earlier deposition reduced by exponential decay ($e^{-\lambda}$).
b Values from [B2]. Units adjusted with conversion factor 0.00869 Gy R^{-1}.
c Corresponds to the parameter D_0. The value is derived from the absorbed dose rate in air per unit deposition density times 0.7 (dose rate in air to effective dose rate conversion factor) times 0.36 (shielding-occupancy factor).
d Includes dose from Rh-106.
e Includes dose from Pr-144.

Table 12
Parameters for calculation of annual effective dose from inhalation of radionuclides in fallout from atmospheric nuclear testing [a]

Radionuclide	*Ratio to ^{90}Sr deposition*	*Transfer factor P_{25} [b] (nSv per Bq m^{-2})*
Mn-54	2.9	0.022
Sr-90	1.0	4.6
Ru-106	7.5	1.7
Sb-125	0.89	0.045
Cs-137	1.5	0.11
Ce-144	15	1.3
Pu-238	0.00046	800
Pu-239	0.011	840
Pu-240	0.0072	840
Pu-241	0.23	12
Am-241	0.0077	920

a The annual dose in a specific year is the transfer factor P_{25} times the deposition density of the radionuclide in that year.
b Derived from the average deposition velocity (1.76 cm s^{-1}) and breathing rate (20 m^3 d^{-1}).

Table 13
Parameters for calculations of annual effective doses from ingestion of radionuclides in fallout from atmospheric testing [a]

Pathway	*Transfer parameter*	^{90}Sr	^{137}Cs
Deposition to diet	b_1 (Bq a kg^{-1} per Bq m^{-2})	0.001	0.0038
	b_2 (Bq a kg^{-1} per Bq m^{-2})	0.001	0.0029
	b_3 (Bq a kg^{-1} per Bq m^{-2})	0.00011	0.000052
	λ' (a^{-1})	0.06	0.03
	P_{23} (Bq a kg^{-1} per Bq m^{-2})	0.0038	0.0084
Diet to body	c (Bq a kg^{-1} per Bq a kg^{-1})	17.5	
	g (Bq a kg^{-1} per Bq a kg^{-1})	3.7	
	λ_b (a^{-1})	0.13	
	P_{34} (Bq a kg^{-1} per Bq a kg^{-1})	47.9	2.6
Body to dose	P_{45} (nSv per Bq a kg^{-1})	290	2500
Diet to dose [b]	P_{35} (nSv per Bq)	27.8	13
Deposition to dose	P_{25} (nSv per Bq m^{-2})	52.4	54.6

a Annual dose in a specific year is the deposition density of ^{90}Sr or ^{137}Cs in that year times the annual component of P_{23} times the annual component of P_{34} times P_{45} plus the residual body burden (for ^{90}Sr) reduced by exponential decay and removal ($e^{-\lambda b}$) times P_{45}.
b Assumes consumption intake of food of 500 kg a^{-1}.

Table 14
Parameters for calculation of annual effective dose from short-lived radionuclides in fallout from atmospheric nuclear testing [a]

Radionuclide	*Half-life (d)*	*Effective dose commitment (μSv)*
Zr-95	64.03	128 [b]
Sr-89	50.55	3.3
Y-91	58.51	2.8
Ru-103	39.25	13
I-131	8.02	51
Ba-140	12.75	16
Ce-141	32.50	1.5
Total		215.6

a Annual effective dose in a specific year is the effective dose commitment from all testing weighted by the fractional fission yield in that year.
b Includes effective dose commitment from Nb-95.

Table 15
Annual effective doses from radionuclides in fallout from atmospheric nuclear testing

Year	Annual effective dose (μSv) [a]											
	Short-lived radionuclides	External					Ingestion			Inhalation	Global		Total
		^{54}Mn	^{106}Ru	^{125}Sb	^{137}Cs	^{144}Ce	^{55}Fe	^{90}Sr	^{137}Cs		^{3}H	^{14}C	
1951	0.01	0.0010	0.0007	0.0002	0.0002	0.0003	0.0002	0.0004	0.002	0.004	0.0		0.02
1952		0.1	0.10	0.03	0.03	0.04	0.03	0.06	0.4	0.6	0.0	0.06	1.4
1953	4.0	0.3	0.2	0.06	0.07	0.07	0.05	0.1	0.8	0.8	0.2	0.14	6.7
1954	19.0	1.1	0.7	0.2	0.3	0.3	0.2	0.5	2.8	3.8	0.7	0.34	29.9
1955	0.004	1.4	1.0	0.4	0.5	0.4	0.2	0.9	4.2	3.7	0.2	0.58	13.4
1956	5.9	1.8	1.3	0.5	0.7	0.5	0.3	1.1	4.8	4.7	0.7	0.81	23.1
1957	11.5	2.0	1.5	0.7	1.0	0.5	0.3	1.4	5.4	4.8	0.6	1.10	30.8
1958	10.5	2.6	1.9	0.9	1.4	0.6	0.4	1.7	6.7	6.7	0.8	1.58	35.8
1959	20.5	3.5	2.6	1.1	1.8	0.9	0.6	2.4	9.3	9.3	0.8	1.94	54.7
1960		2.4	1.9	1.1	2.0	0.6	0.3	2.3	6.8	3.2	0.4	1.99	22.9
1961		2.1	1.6	1.0	2.2	0.5	0.3	2.0	4.3	3.9	0.7	2.92	21.4
1962	36.3	4.2	3.0	1.5	2.8	1.1	0.7	3.0	10.3	12.8	7.2	5.51	88.4
1963	82.5	7.5	5.3	2.3	4.0	1.9	1.4	5.0	20.5	22.0	2.7	7.39	162.5
1964		7.3	5.4	2.6	4.8	1.8	1.1	6.0	21.1	15.6	1.6	7.71	74.9
1965	0.004	5.4	4.2	2.4	5.2	1.3	0.7	5.2	13.6	8.5	1.2	7.54	55.3
1966	0.2	3.4	2.8	2.1	5.3	0.8	0.3	4.4	7.4	4.0	1.0	7.14	38.8
1967	2.7	2.1	1.8	1.7	5.3	0.5	0.2	3.8	4.0	2.1	0.8	6.59	31.5
1968		1.5	1.3	1.5	5.3	0.3	0.1	3.5	3.2	2.2	0.6	6.05	25.6
1969	5.6	1.2	1.0	1.2	5.3	0.3	0.1	3.4	3.2	2.2	0.6	5.48	29.6
1970	4.3	1.2	0.9	1.1	5.3	0.3	0.2	3.3	3.4	2.5	0.4	5.03	27.9
1971	4.3	1.2	0.9	1.0	5.3	0.3	0.2	3.2	3.6	2.6	0.4	4.64	27.6
1972	1.7	0.9	0.7	0.8	5.3	0.2	0.1	3.1	2.8	1.4	0.3	4.34	21.6
1973	2.0	0.5	0.4	0.7	5.2	0.1	0.04	2.7	1.7	0.5	0.3	4.02	18.2
1974	0.6	0.5	0.4	0.6	5.2	0.1	0.07	2.6	1.7	1.2	0.2	3.77	16.9
1975	0.2	0.4	0.3	0.5	5.1	0.10	0.05	2.5	1.7	0.7	0.2	3.54	15.3
1976		0.3	0.2	0.4	5.0	0.07	0.03	2.3	1.3	0.4	0.1	3.26	13.3
1977	2.9	0.3	0.3	0.3	4.9	0.08	0.05	2.2	1.3	0.8	0.2	3.06	16.4
1978		0.4	0.3	0.3	4.9	0.09	0.06	2.1	1.6	0.9	0.1	2.86	13.6
1979		0.2	0.2	0.3	4.8	0.06	0.03	2.0	1.3	0.3	0.1	2.63	11.9
1980		0.2	0.2	0.2	4.7	0.04	0.02	1.8	1.0	0.3	0.1	2.53	11.0
1981	0.6	0.2	0.1	0.2	4.6	0.04	0.02	1.7	0.9	0.3	0.1	2.48	11.2
1982		0.09	0.07	0.1	4.5	0.02	0.007	1.6	0.8	0.1	0.06	2.43	9.8
1983		0.04	0.04	0.1	4.4	0.009	0.002	1.5	0.6	0.020	0.05	2.38	9.2
1984		0.02	0.02	0.09	4.3	0.004	0.0006	1.4	0.6	0.006	0.04	2.33	8.8
1985		0.010	0.01	0.07	4.2	0.002	0.0002	1.3	0.6	0.002	0.04	2.28	8.5
1986		0.004	0.006	0.05	4.1	0.0008	0.00003	1.2	0.5		0.03	2.24	8.2
1987		0.002	0.003	0.04	4.0	0.0003		1.2	0.5		0.03	2.20	7.9
1988		0.0009	0.001	0.03	3.9	0.0001		1.1	0.5		0.03	2.15	7.7
1989		0.0004	0.0008	0.02	3.8	0.00005		1.0	0.5		0.02	2.11	7.5
1990		0.0002	0.0004	0.02	3.7	0.00002		1.0	0.5		0.02	2.07	7.3

Table 15 (continued)

Year	Annual effective dose (μSv) [a]												
	Short-lived radionuclides	External					Ingestion			Inhalation	Global		Total
		^{54}Mn	^{106}Ru	^{125}Sb	^{137}Cs	^{144}Ce	^{55}Fe	^{90}Sr	^{137}Cs		^{3}H	^{14}C	
1991		0.00008	0.0002	0.02	3.6	0.00001		0.9	0.5		0.02	2.03	7.1
1992		0.00003	0.00010	0.01	3.6			0.8	0.4		0.02	1.99	6.9
1993		0.00002	0.00005	0.009	3.5			0.8	0.4		0.02	1.94	6.7
1994		0.00001	0.00003	0.007	3.4			0.7	0.4		0.01	1.90	6.5
1995			0.00001	0.005	3.3			0.7	0.4		0.01	1.86	6.3
1996			0.00001	0.004	3.2			0.7	0.4		0.01	1.82	6.1
1997				0.003	3.2			0.6	0.4		0.01	1.78	6.0
1998				0.003	3.1			0.6	0.4		0.01	1.74	5.8
1999				0.002	3.0			0.5	0.4		0.01	1.70	5.7
1945-1999	215.4	56.4	42.9	28.2	175.1	13.8	8.2	94.0	159.5	122.8	23.3	144.0	1084
2000-2099				0.007	117.3			8.7	11.3		0.1	120	257.4
2100-2199					11.8			0.02	0.5			50	62.3
2200→∞					1.3			0.00005	0.03			2180	2181
1945→∞	215.4	56.4	42.9	28.2	305.4	13.8	8.2	102.8	171.3	122.8	23.4	2494	3585

a Population-weighted global average.

Table 16
Local doses from atmospheric nuclear testing

Test site	*Population*	*Maximum absorbed dose in thyroid of children (Gy)*	*Maximum effective dose (Sv)*	*Collective effective dose (man Sv)*	*Ref.*
United States					
Nevada	180,000	1		500 [b]	[A1]
Pacific [a]	245	200	1.9	160	[L4]
Former USSR					
Semipalatinsk	10,000	20		4600	[T1]
United Kingdom					
Australian sites [c]				700	[W1]

a Exposures from Bravo test of 28 February 1954 to residents of Rongelap, Utrik and Ailinginae atolls.
b External exposure only.
c Maralinga, Emu, Monte Bello Island.

Table 17
Distribution of cumulative effective doses to individuals exposed in local areas downwind of the Nevada test site
[A1]

Effective dose (mSv)		*Number of individuals*		*Collective effective dose (man Sv)*	
Range	*Mean* [a]	*1951-1958*	*1961-1963*	*1951-1958*	*1961-1963*
<0.06-0.6	0.2	61,000	180,000	12	36
0.6-3	1.3	80,000	480	104	0.6
3-6	4.2	19,000	0	80	
6-30	13	20,000	0	260	
30-60	42	520	0	22	
60-90	73	45	0	3.2	
Total (rounded)		180,000	180,000	460	40

a Assumed to be geometric mean of range.

Table 18
Cumulative exposures in contaminated areas downwind of the Semipalatinsk test site

District	*Population in 1960*	*Average effective dose [a] (mSv)*	*Collective effective dose [a] (man Sv)*
Kazakhstan [G8]			
Dolon	906	4470	4050
Sarzhal	832	2460	2050
Cheremushky	531	2250	1190
Mostik	637	2250	1430
Kanonerka	1227	1790	2200
Karaul	2335	880	2050
Kainar		680	
Znamemka	903	620	560
Chubertansky Novoshubinsky Borodulikhinski Chersky Zharminsky Ayaguzky Semipalatinsk City	163000	70-340	
Makanchinsky Urdjarsky Taskeskensky Kolpektinsky Aksuatsky		<70	
Semipalatinsk region	811,000		
Altai region [L5]			
Uglovskoye	4,500	490	2,210
Rubtsovsk	133,500	23	3,110
Lokot	30,500	59	1,790
Zmeinogorsk	16,800	42	710
Kurya	16,200	36	590
Krasnoshchekovo	27,500	8.9	250
Ust-Kalmanka	17,600	7.4	130
Pospelikha	27,000	12	310
Petropalovskoye	34,400	3.8	130
Shipunova	33,900	3.4	120
Zarinsk	42,400	3.4	150
Total	937,200	12	11,000

a External exposure only.

Table 19
Exposures in settlements of Altai region downwind of the Semipalatinsk test site following nuclear test of 29 August 1949
[L5]

Settlement	*Distance from test site*	*Thyroid dose (Gy)*		*Effective dose [a] (mSv)*
		Children	*Adults*	
Topolnoye	180	28	7.0	490
Nanmovka		30	7.5	520
Lokot	240	16	40.	280
Kurya	330	3.8	0.95	60
Petropavlovskoye	470	0.4	0.10	6
Biysk	560	0.2	0.05	3
Solton	640	0.2	0.05	3

a External exposure only.

Table 20
Estimated local exposures from atmospheric nuclear tests conducted by France at the South Pacific test site
[B8]

Location	*Date of test*	*Population*	*Effective dose (mSv)*				*Collective effective dose (man Sv)*
			External	*Inhalation*	*Ingestion*	*Total*	
Gambier Islands	2 July 1966 8 August 1971	40 68	3.4 0.9	0.18 0.002	1.9 0.24	5.5 1.2	0.2 0.5
Tureia Atoll	2 July 1967 12 June 1971	516 545	0.7 0.9	0.023 0.003	0.17 0.043	0.9 1.3	0.7 0.08
Tahiti (Mahina)	17 July 1974	84,000	0.6	0.08	0.06	0.8	67
Total							70

Table 21
Effective dose estimates from external exposures at locations 400-800 km downwind of the Lop Nor test site
[Z1]

City	*Population*	*Distance from test site (km)*	*Absorbed dose in air (mGy)*	*Effective dose [a] (mSv)*
Xihu			0.07	0.02
Anxi		500	0.06	0.02
Tashi		510	0.10	0.03
Qiaowan		560	0.14	0.04
Yumenzhen		600	0.12	0.03
Yumanshi			0.02	0.006
Jinta		740	0.45	0.11
Jiayuguan		720	0.44	0.11
Average			0.18	0.044

a External exposure only.

Table 22
Underground nuclear tests

Year	*Number of tests*					
	China	*France*	*India*	*United Kingdom*	*United States*	*USSR*
1951					1	
1955					1	
1957					5	
1958					15	
1961		1			10	1
1962		1		2	57	1
1963		3			45	
1964		3		2	48	9
1965		4		1	39	15
1966		1			49	19
1967					42	23
1968					72	23
1969	1				61	24
1970					60	21
1971					28	29
1972					32	31
1973					27	22
1974			1	1	25	27
1975	1	2			23	35
1976	1	5		1	20	27
1977		9			23	36
1978	1	11		2	20	55
1979		10		1	15	52
1980		12		3	14	43
1981		12		1	16	37
1982	1	10		1	18	34
1983	2	9		1	19	37
1984	2	8		2	18	52
1985		8		1	17	10
1986		8		1	14	
1987	1	8		1	16	39
1988	1	8			18	29
1989		9		1	15	11
1990	2	6		1	10	8
1991		6		1	9	
1992	2				8	
1993	1					
1994	2					
1995	2	5				
1996	2	1				
Total	22	160	1	24	910	750
All countries	1867					

Table 23
Summary of nuclear testing

Country	Number of tests			Yield (Mt)		
	Atmospheric	Underground	Total	Atmospheric	Underground	Total
China	22	22	44	20.7	1	22
France	50 [a]	160	210	10.2	3	13
India	-	1	1			
United Kingdom	33 [b]	24	57	8.1	2	10
United States	217 [c]	910	1127	154	46	200
USSR	219	750	969	247	38	285
All countries	541	1867	2408	440	90	530

a Includes 5 safety tests.
b Includes 12 safety tests.
c Includes 22 safety tests and 2 combat explosions.

Table 24
Radionuclide releases and estimated local exposures from nuclear weapons material production and fabrication plants in the United States

Location	Release period	Airborne release (GBq)	Liquid release (GBq)	Cumulative effective dose (mSv)		Reference
				Airborne	Liquid	
Fernald	1954-1980	310,000 kg (U)	82,000 kg (U)			[M3]
Oak Ridge	1942-1984		25,400 (^{137}Cs)			[W5]
Rocky Flats	1953-1983 (routine) 1957 (fire) 1965-1969 (storage area)	8.8 (U) / 1.7 (Pu) 1.9 (Pu) 260 (Pu)		0.0015 0.013 0.072		[R3] [M4] [M5]
Hanford	1944-1987	27,300,000 (^{131}I)	481,000,000 (^{24}Na)	12	15	[S3, H4]
Savannah River	1954-1989	140 (Pu)	23 (Pu)	0.12	0.0024	[C1]

Table 25
Releases of radioactive materials associated with the early operation of the materials production complex at Chelyabinsk-40 in the eastern Urals region of the Russian Federation

Circumstances of release	Time period	Radionuclide composition (%)					Total activity release (PBq)
		^{90}Sr	^{95}Zr	^{106}Ru	^{137}Cs	^{144}Ce	
Routine operation Atmospheric effluents Liquid effluents to Techa River[a]	 1948-1956 1949-1956	 11.6	 13.6	 25.9	 12.2	 	 100
Accident at waste storage site	1957	5.4	24.9	3.7	0.036	66.0	74
Resuspension from shoreline of Lake Karachay	1967	34			48	18	0.0 22

a Radionuclide composition included additionally ^{89}Sr (8.8%) and other (27.9%).

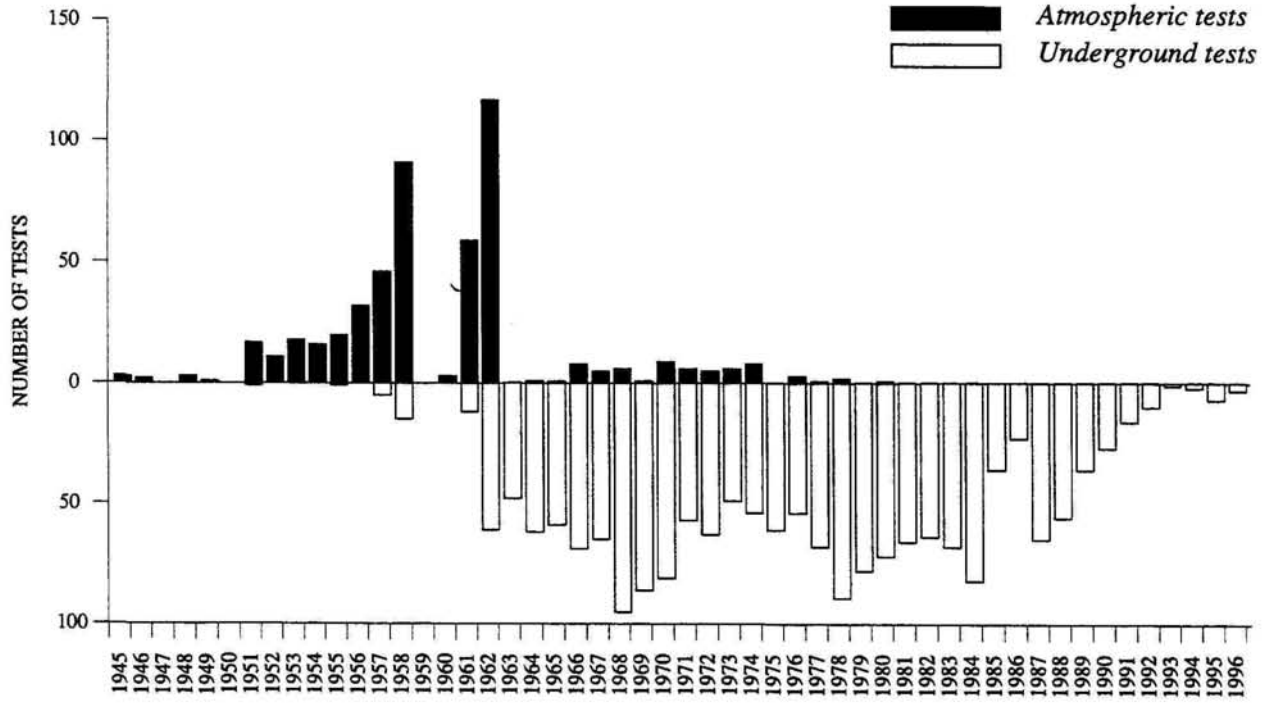

Figure I.
Number of nuclear tests.

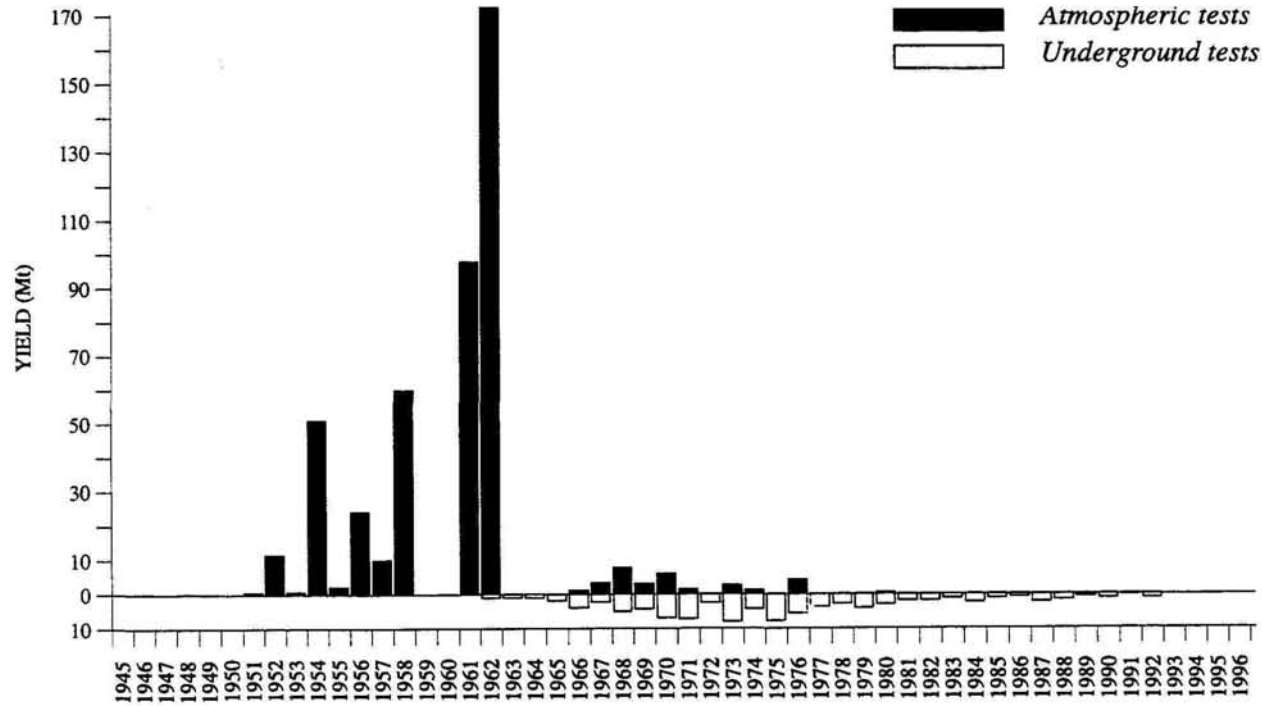

Figure II.
Total yield of nuclear tests

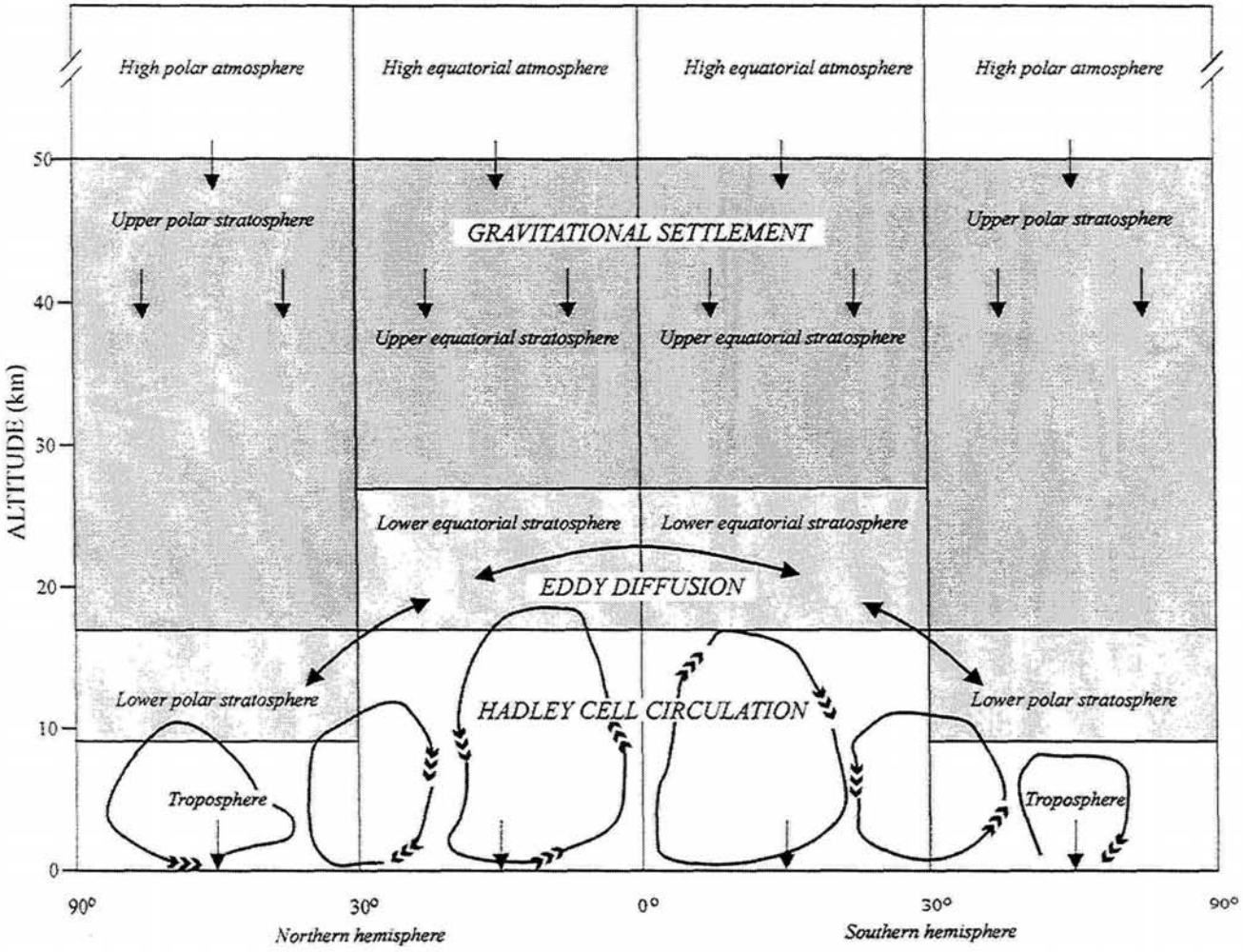

Figure III.
Atmospheric regions and the predominant atmospheric transport processes.

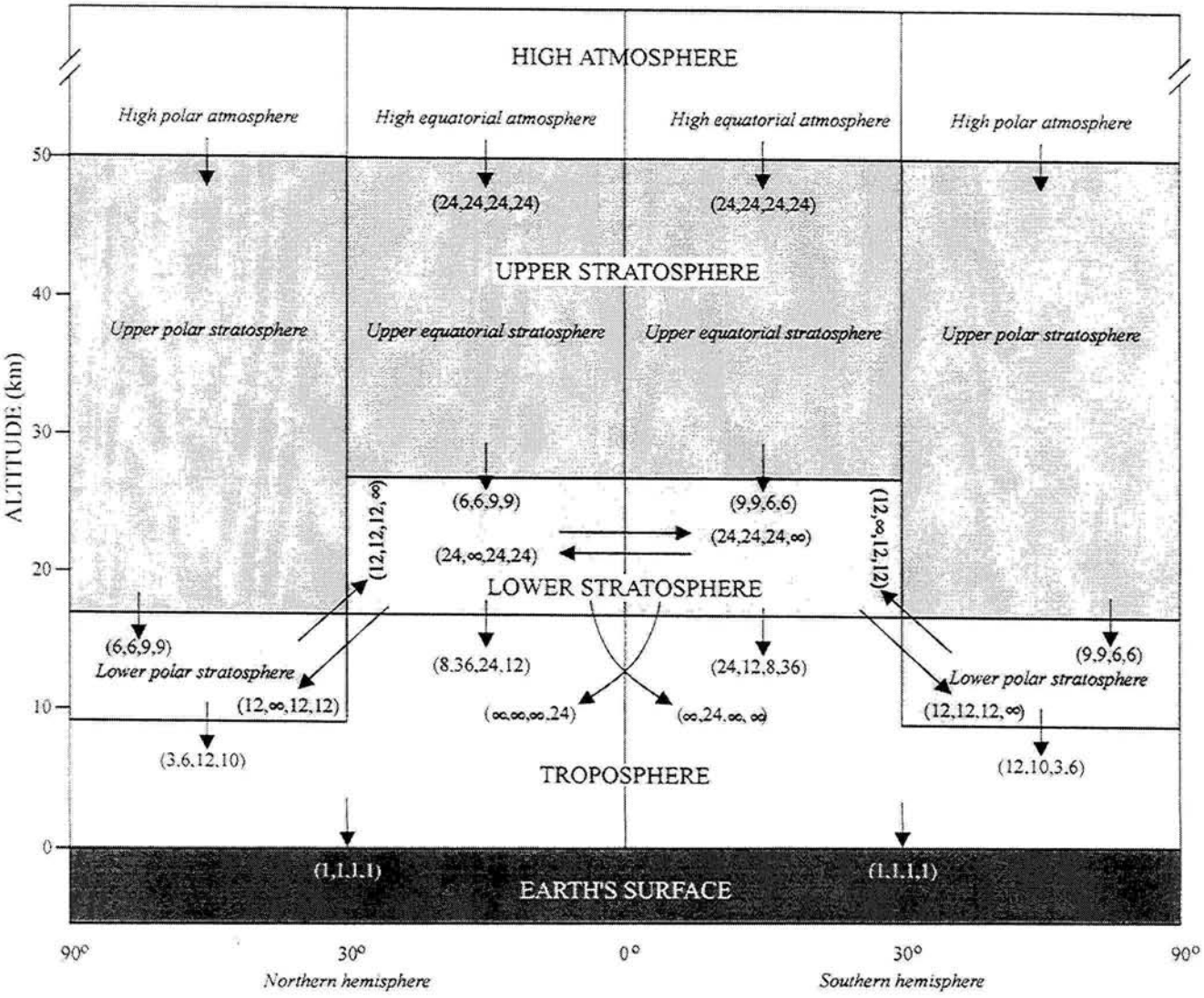

Figure IV.
Schematic diagram of transfers between atmospheric regions and the earth's surface considered in the empirical atmospheric model [B1].
The numbers in parentheses are the removal half-times (in months) for the yearly quarters in the following order: March-April-May, June-July-August, September-October-November, December-January-February.

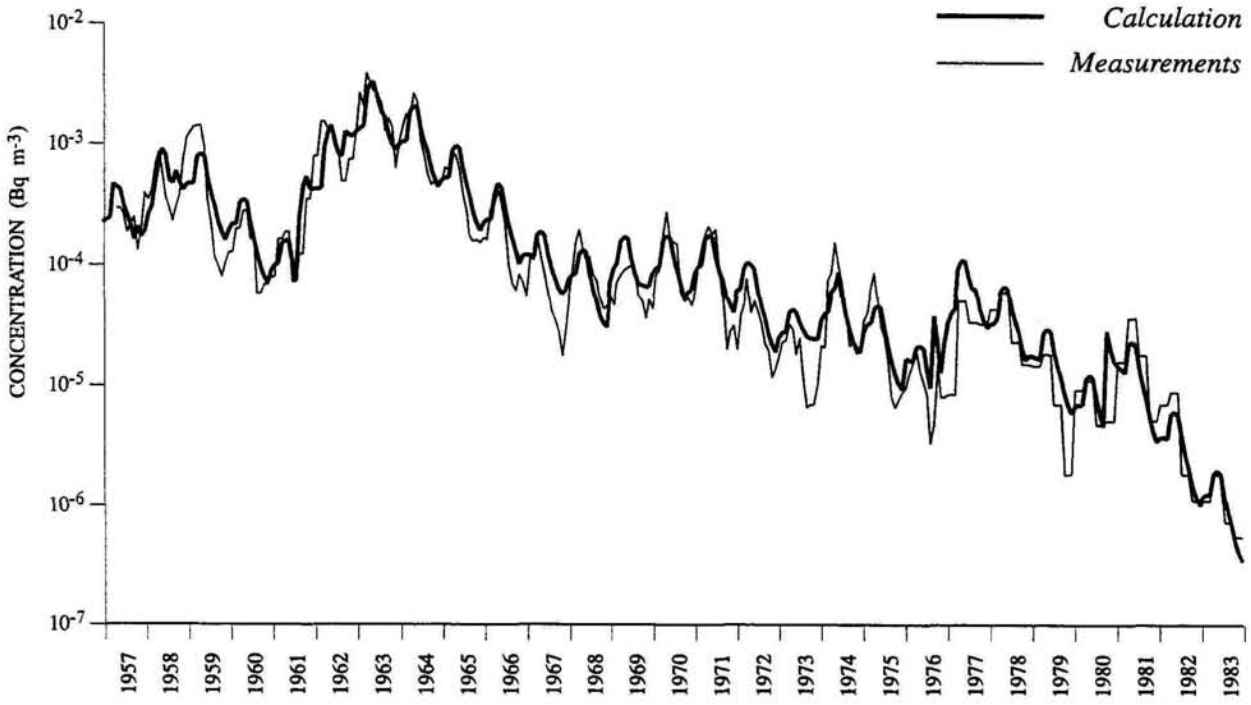

Figure V.
Strontium-90 concentration in air in the mid-latitude region of the northern hemisphere.
Averaged measurements at several sites compared with results of atmospheric model calculations.

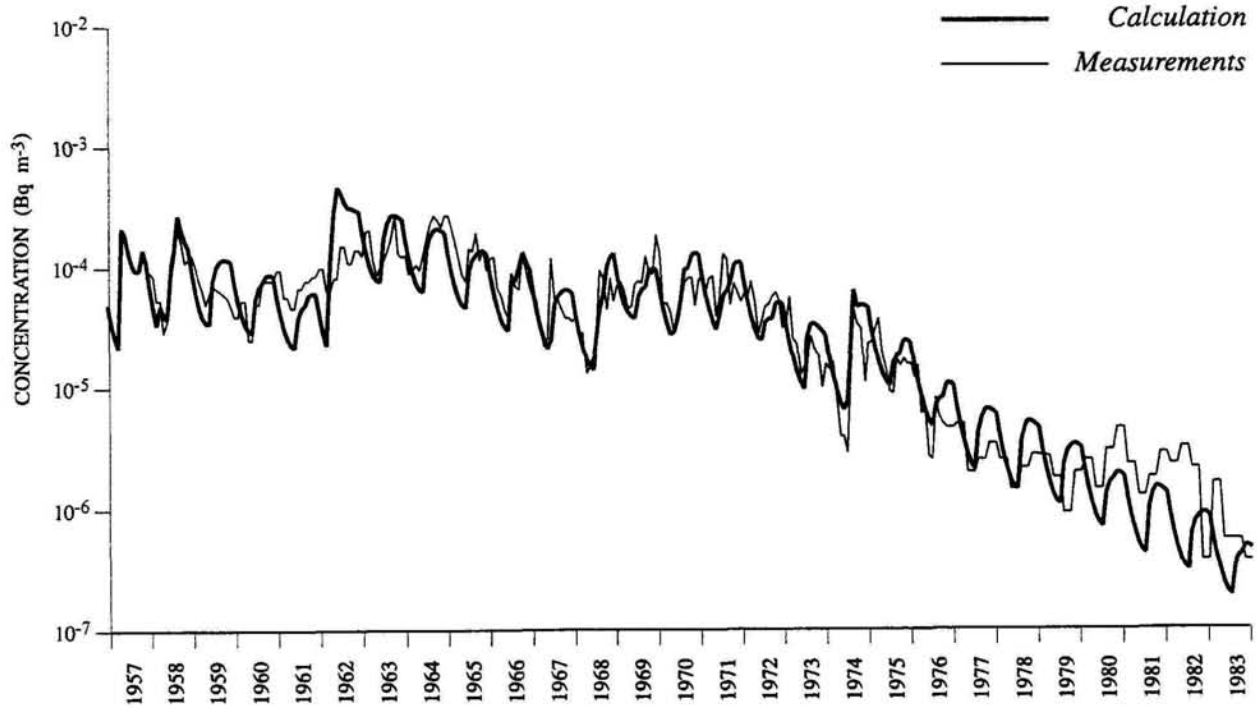

Figure VI.
Strontium-90 concentration in air in the mid-latitude region of the southern hemisphere.
Averaged measurements at several sites compared with results of atmospheric model calculation.

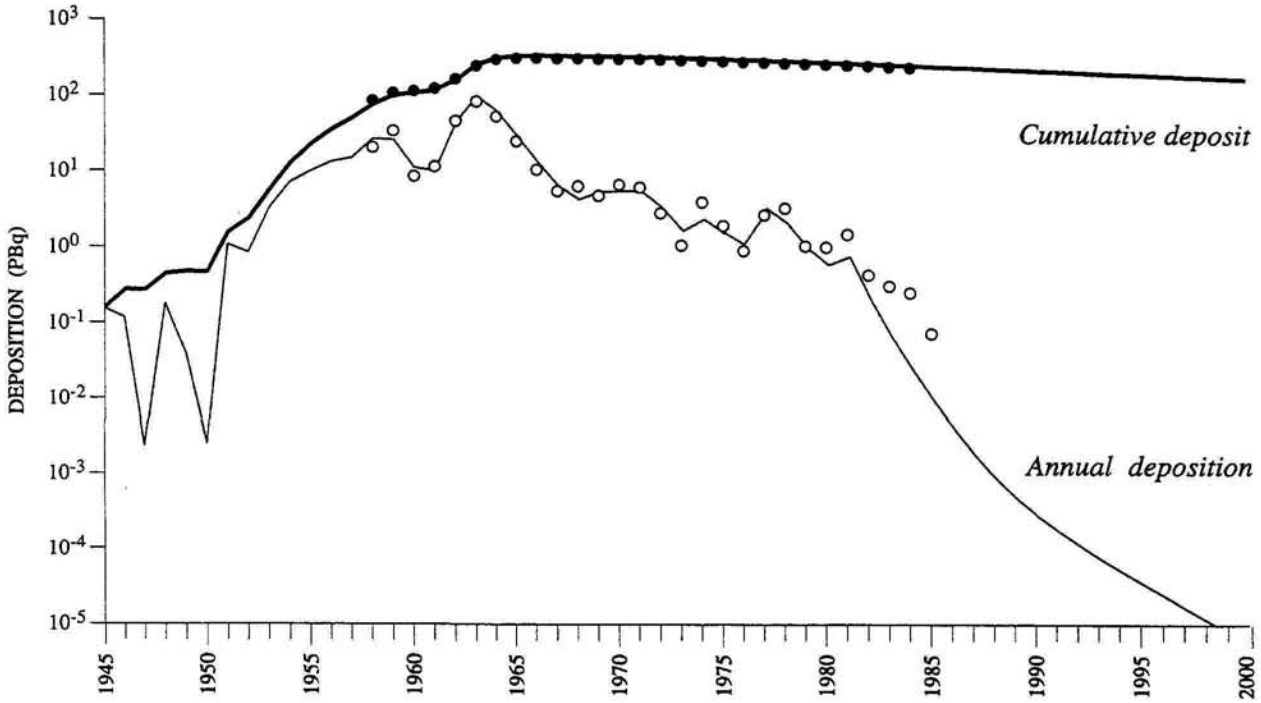

Figure VII.
Deposition of strontium-90 in the northern hemisphere.
Results of global network measurements (points) and atmospheric model calculations (lines).

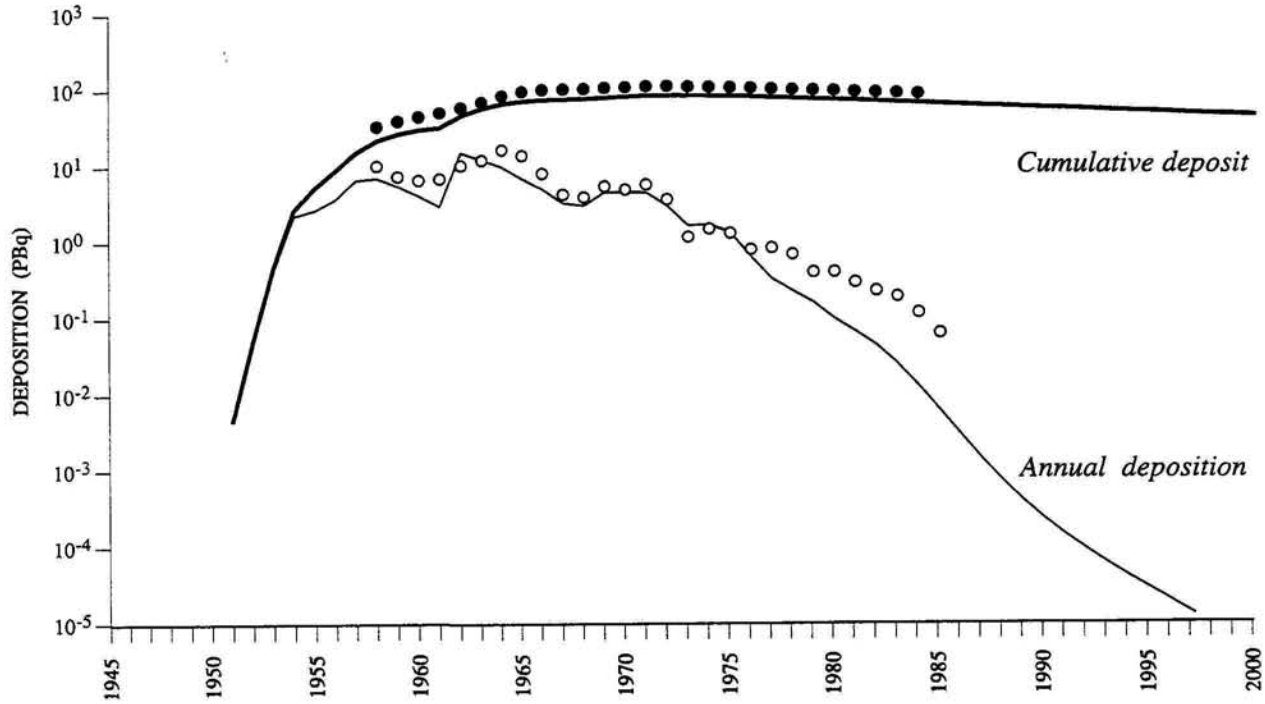

Figure VIII.
Deposition of strontium-90 in the southern hemisphere.
Results of global network measurements (points) and atmospheric model calculations (lines).

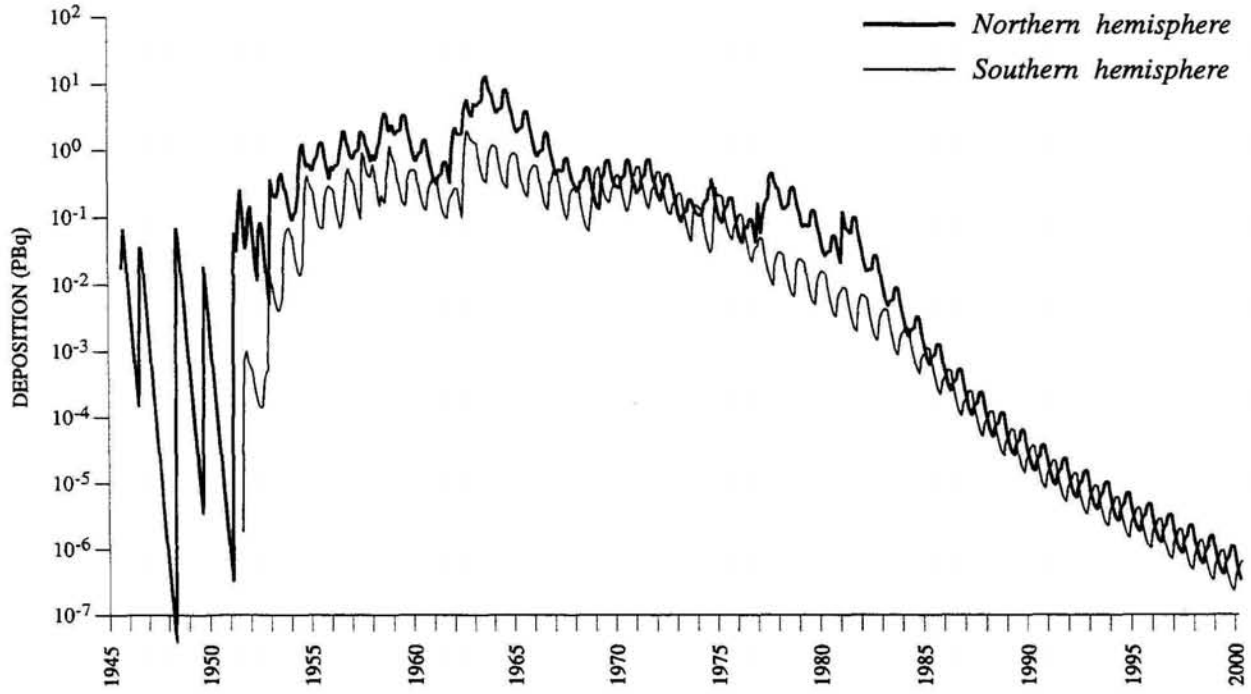

Figure IX.
Monthly deposition of strontium-90 in the northern and southern hemisphere. Results calculated from amounts produced in individual tests and dispersed according to the atmospheric model.

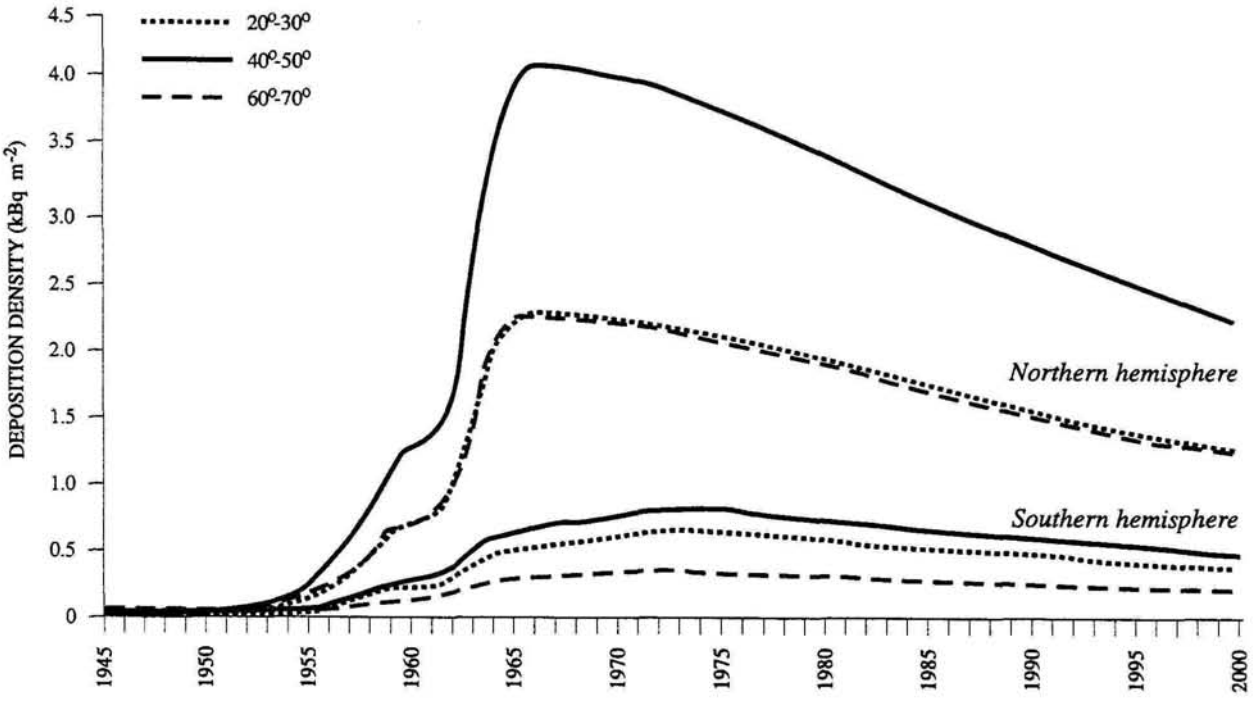

Figure X.
Caesium-137 deposition density in the northern and southern hemispheres calculated from fission production amounts with the atmospheric model.

Figure XI.
Annual deposition of zirconium-95 in the northern and southern hemispheres. Results calculated from amounts produced in individual tests and dispersed according to atmospheric model.

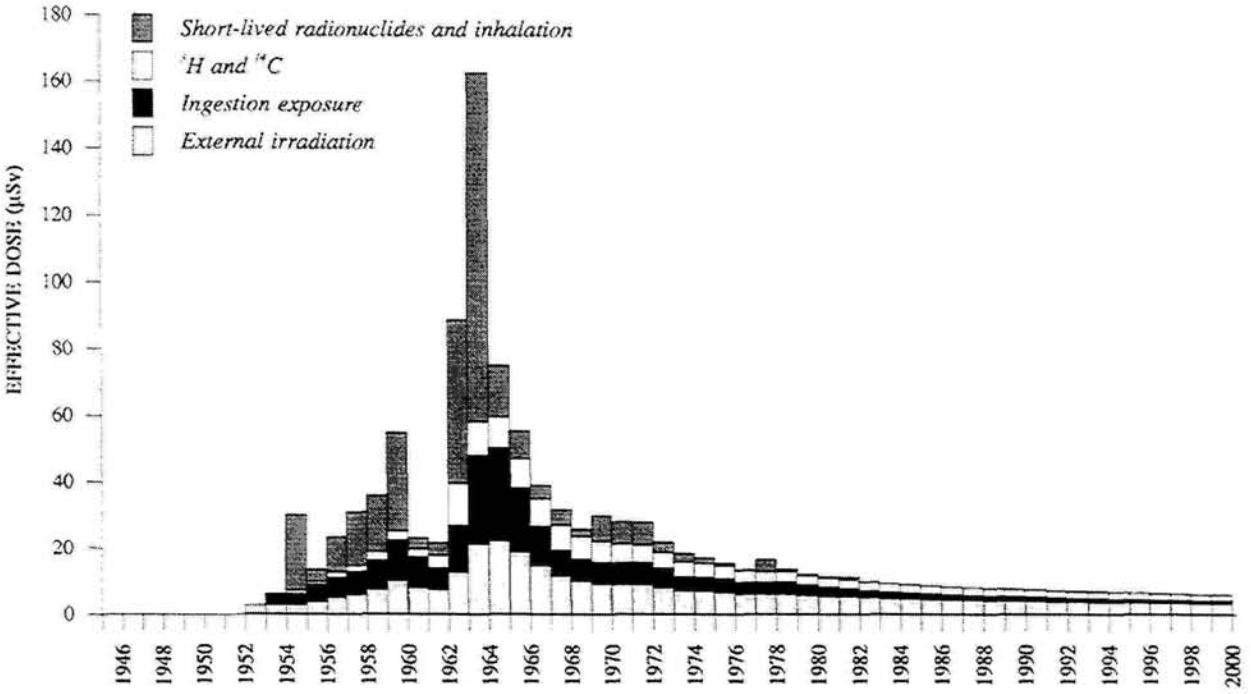

Figure XII.
Annual effective dose from the main pathways of exposure to radionuclides produced in atmospheric nuclear testing.

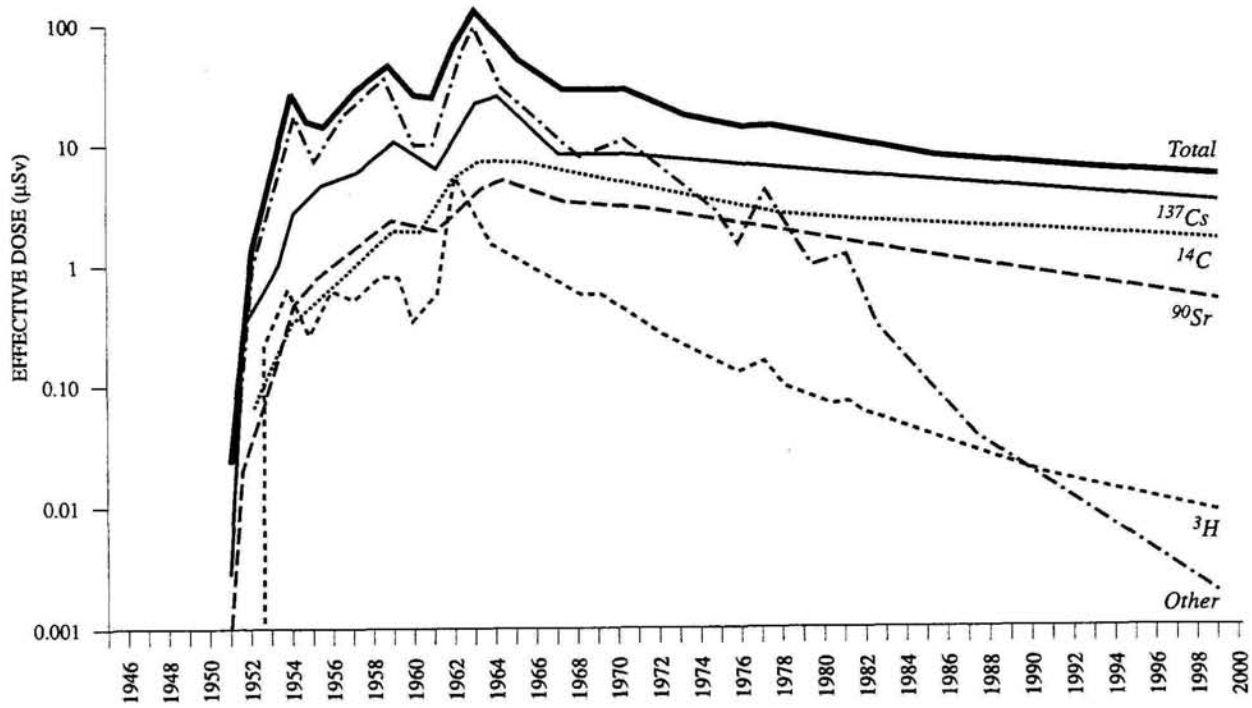

Figure XIII.
Annual effective dose from radionuclides produced in atmospheric nuclear testing.

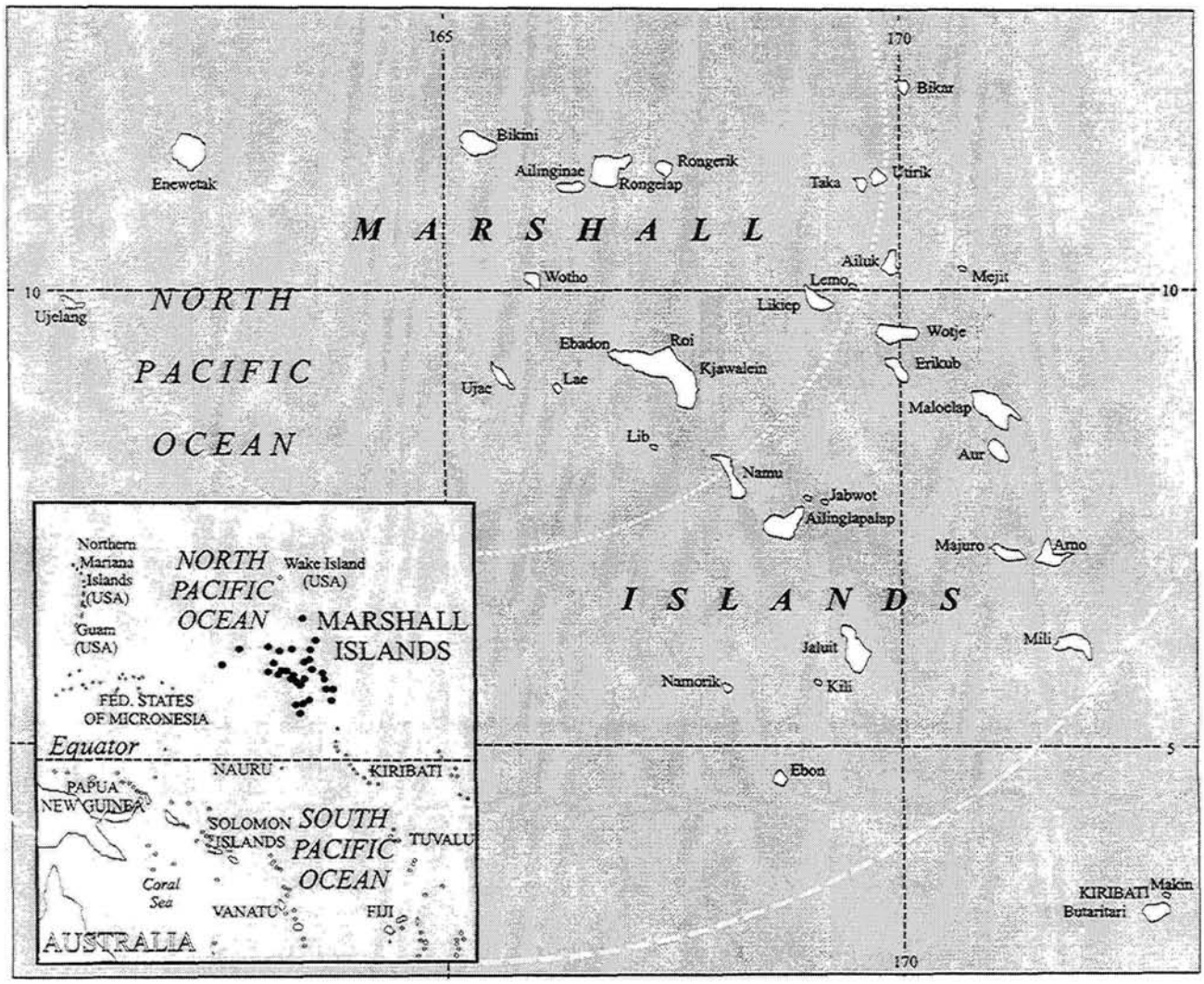

Figure XIV.
Bikini and Enewetak test sites.
The inner dotted circle indicates a distance of 500 km, the outer dashed circle 1000 km from the Bikini test site.

Figure XV.
Lop Nor and Semipalatinsk test sites.
The inner dotted circle indicates a distance of 500 km, the outer dashed circle 1000 km from the test sites.
The measurement areas in Gansu Province (for Lop Nor) and Altai Region (for Semipalatinsk) are shown within the elliptical areas.

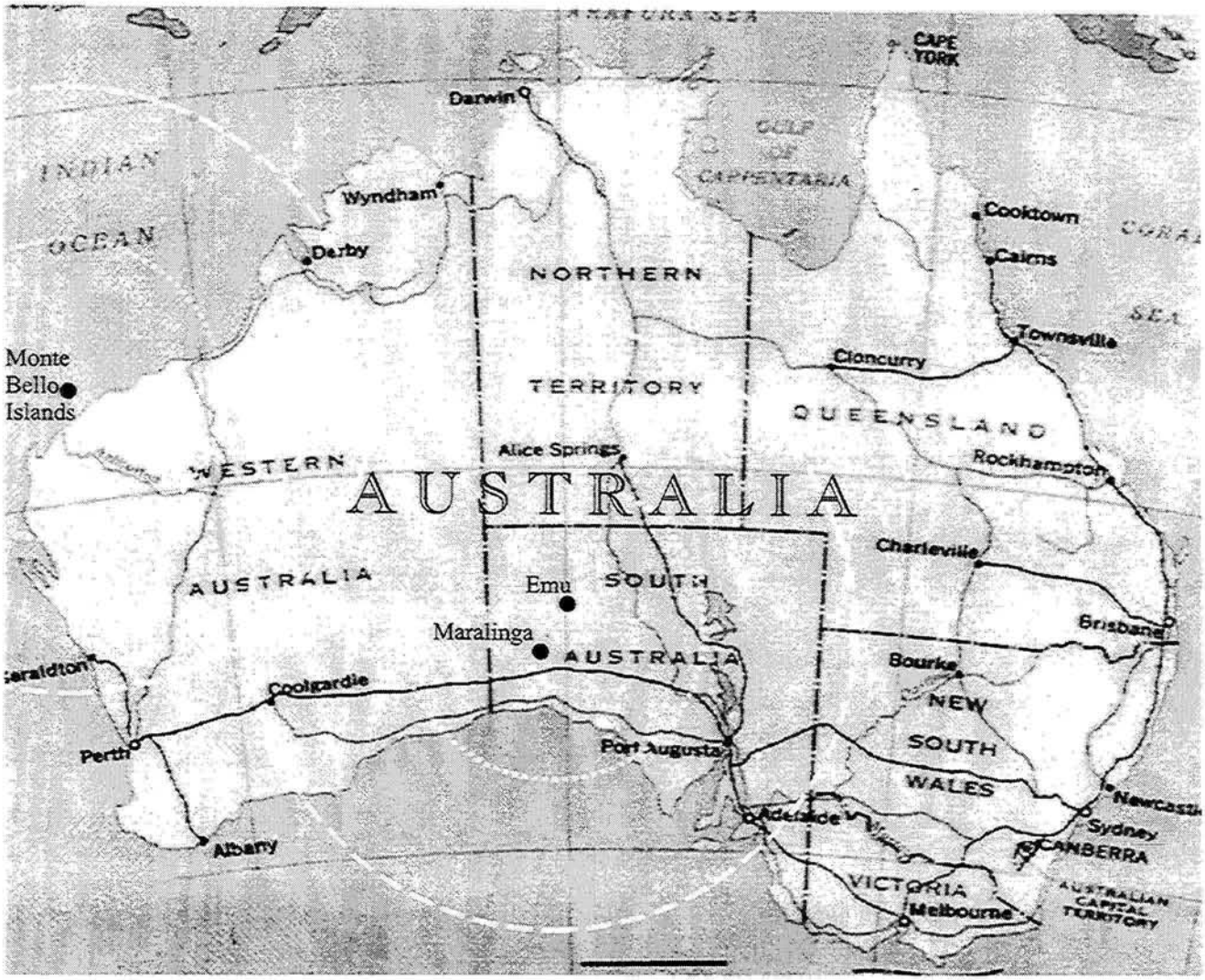

Figure XVI.
Maralinga, Emu and Monte Bello Islands test sites.
The inner dotted circle indicates a distance of 500 km, the outer dashed circle 1000 km from the test sites.