ANNEX B

Exposures from man-made sources of radiation

CONTENTS

INTRODUCTION

1. Several practices and activities of man involving the production and use of radionuclides have resulted in releases of radioactive materials to the environment. Some of these activities have ceased, such as testing of nuclear weapons in the atmosphere, and some are continuing, such as electrical energy generation by nuclear reactors and radioisotope production and usage. In carrying out these activities, several accidents have occurred at nuclear installations and waste storage sites and in the transport of weapons or nuclear materials, causing in some cases significant contamination of the local environment. The purpose of this Annex is to evaluate and compare the collective doses to the local and global populations from these various man-made sources of radiation exposures.

2. Most of these subjects have been dealt with in the past by the Committee in separate assessments. Atmospheric nuclear testing and nuclear power production, in particular, have been extensively analysed. In this Annex, the evaluation procedures are summarized, and the dose calculations are extended. For nuclear power production, estimates of average releases per unit electrical energy generated are combined with data on energy generated by all reactors to evaluate the total releases of radionuclides worldwide and the collective dose from the beginning of this practice. For the first time since the Committee began its assessments of exposures from nuclear power production, there is complete reporting of radionuclides released from all reactors in operation in all countries for the latest evaluation period. The Committee acknowledges the cooperation of a great many scientists and officials who have made these data available for this evaluation.

3. A number of sources cannot be so systematically evaluated. These include releases from the use of radioisotopes in industries or hospitals, in which only trace contamination and very low doses result, and in the military fuel cycle, for which data have been restricted and the dose evaluations have therefore remained incomplete and uncertain. In this Annex the Committee considers these various sources to the extent possible to provide a comprehensive assessment of exposures from man-made sources.

4. Exposures from accidents of environmental significance are summarized here. Most of the doses resulting from these sources were evaluated in detail at the time of occurrence, in particular the doses

throughout the northern hemisphere from the Chernobyl accident, presented in the UNSCEAR 1988 Report [U1]. However, further data are becoming available on some accidents that occurred many years ago, when the full disclosure of details was not possible. This information is considered here to provide indications of the population doses that were received. Evaluations of doses to populations living near nuclear test sites have been undertaken, and some dose estimates have been provided in published reports. These results are also included in this Annex. For the various sources, the collective doses evaluated are those committed by the specific releases. If less than the complete dose commitments have been evaluated, the integration times are specified in the discussions for each type of source.

I. ATMOSPHERIC NUCLEAR TESTING

5. A very important concern of the Committee since its inception has been to evaluate the exposures caused by nuclear explosions in the atmosphere. The first atmospheric nuclear explosions took place in 1945. Subsequent testing of nuclear weapons in the atmosphere occurred until 1980, with periods of intensive testing in the years 1952-1954, 1957-1958 and 1961-1962. A limited nuclear test ban treaty (Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under the Water) was signed in August 1963, and much less frequent testing in the atmosphere occurred subsequently.

6. Exposures from nuclear weapons tests in the atmosphere have been reviewed by the Committee in all its previous reports until the cessation of the practice [U3-U10]. As there have been no tests in the atmosphere since October 1980, the most recent analysis prepared by the Committee, in the UNSCEAR 1982 Report [U3], remains complete and valid. These results and the generally applicable methodologies of exposure assessment are summarized here.

7. The basic quantity of radiation dose evaluations for radionuclides released to the environment is the dose commitment. Dose commitments are calculated from the input of radionuclides into the environment, using transfer coefficients relating appropriate time-integrated quantities in environmental compartments and in man. Schematic representation of the methodology used by the Committee for evaluating exposures from radionuclides released in nuclear testing is illustrated in Figure I. Transfer coefficients are used to relate input, integrated concentrations of radionuclides and dose in successive environmental compartments. For example, the transfer coefficient from diet to tissue is the ratio of the integrated concentration of the radionuclide in tissue to that in diet and is designated P_{34}. Transfers linking input to dose are determined by the sequential multiplication of transfer coefficients. Transfers by parallel pathways are assumed to be independent and are thus additive. For the transfers indicated in Figure I, the dose commitment for a specific radionuclide and a given tissue, D_c, due to an environmental input A_0 into the atmosphere is given by

$$D_c = P_{01}[P_{12}P_{23}P_{34}P_{45} + P_{14}P_{45} + P_{15} + P_{12}P_{25}]A_0 \quad (1)$$

8. In this formula the transfer coefficient P_{01} is the integrated concentration of a radionuclide in air at a specified location or averaged for a broader region, divided by the amount released. The first term in the brackets relates the subsequent transfer to deposition, diet, tissue and dose via ingestion. The second term (P_{14} P_{45}) is the transfer from the atmosphere to tissue and dose via inhalation. The third term (P_{15}) accounts for direct (cloud gamma) irradiation from the radionuclide in air. The fourth term is the component of external irradiation from radionuclides deposited on the ground. Some minor pathways (e.g., resuspension) have not been indicated in Figure I, but these are taken into account in determining the integrated concentrations in the compartments. To this extent, the model indicates compartment interrelationships rather than mechanical transfer pathways. Although the terminology was developed for evaluations of doses from radionuclides produced in atmospheric nuclear testing, the methodology is generally applicable to any source of release of radionuclides to the air or terrestrial environment.

A. ENVIRONMENTAL INPUT

9. A nuclear device derives its explosive energy, usually expressed in kilotonnes or megatonnes of TNT equivalent, from one or both of two nuclear processes: fission of the heavy nuclides ^{235}U and ^{239}Pu in a chain reaction and fusion of the hydrogen isotopes deuterium and tritium in a thermonuclear process. Fission produces a whole spectrum of different radioactive nuclides, while fusion in principle creates

only tritium. However, because a thermonuclear device needs high pressures and temperatures to ignite it, in practice a fission device is needed as a primary stage to provide these conditions. Also in practice, the nuclear reactions do not proceed to ultimate completion, so some residual amounts of tritium will also remain. Thus, the explosion of a fusion charge always implies that at least some residual radioactive material is released. Many thermonuclear devices also produce large amounts of radioactive debris in a second fission stage, where high energy neutrons from the fusion reactions are utilized to split the atoms of a ^{238}U blanket. In some fission charges a small thermonuclear stage is used primarily to make neutrons and boost the utilization of the fissile material.

10. The exact composition of products of the fission process depends on the mixture of fissioning nuclides (^{235}U, ^{239}Pu and ^{238}U) and on the neutron energies involved. However, for the purpose of estimating dose commitments, it is sufficient to use average production values per unit fission yield. These are dominated by the ^{238}U high-energy neutron fission mode, as this type of fission was the predominant one in past atmospheric testing.

11. Neutron activation products are produced in significant amounts in fusion explosions from reactions of neutrons with surrounding materials, such as nitrogen in the air and the construction materials of the device. One very important such product is ^{14}C, which is made in the $^{14}N(n,p)^{14}C$ reaction in the atmosphere. The fusion yields are thus of interest for estimating doses from certain radionuclides. Fusion yields are also important, as they are the second part of the total yield, which governs the altitude to which the nuclear cloud rises and, as a result, the time delay before the debris reaches man.

12. A total of 520 atmospheric nuclear explosions (including 8 underwater) have occurred at a number of locations [D2, D8, Z1]. Based on a survey of published estimates of nuclear yields of different tests and measurements of deposited amounts of radioactive materials, Bennett [B5] compiled a list of individual yields of atmospheric nuclear explosions and the partitioning of debris between different parts of the atmosphere. As accurate data on individual tests have not generally been available, this information is of course somewhat uncertain. Summed yields during certain periods of time, however, do agree with reported total yields for these time intervals, and the integrated depositions of long-lived fission products are reasonably consistent with the estimates. The estimates of fission, fusion and total yields exploded in the atmosphere for each year since 1945 are illustrated in Figure II.

13. There were two main periods when most of the radioactive debris produced in nuclear explosions was injected into the atmosphere, namely 1952-1958 and 1961-1962. About 42% of all fission yield in the atmosphere was exploded in the former period and 47% in the latter, adding up to 89% for the 11-year period from 1952 through 1962. The corresponding numbers for fusion yield are 25% and 72%, respectively, giving a total of 97% for the 1952-1962 period. Less than 0.5% of the total fission yield and completely insignificant amounts of fusion yield were exploded before 1952, leaving 11% and 3%, respectively, for the period since 1962. About 90% of the fission yield was due to explosions in the northern hemisphere.

14. The total explosive yield from past atmospheric nuclear weapons tests amounts to 545 Mt, consisting of 217 Mt from fission and 328 Mt from fusion. The contributions of local, tropospheric and stratospheric fallout to total fallout are 12, 10 and 78%, respectively. Local fallout, which is loosely defined as that part of the debris that deposits on the ground in the vicinity of the test site, has not previously been considered by the Committee in its dose assessments because nuclear weapons tests were conducted in isolated areas.

15. The major radionuclides produced in atmospheric nuclear testing from the standpoint of doses delivered are listed in Table 1, along with the basic data of radioactive half-life, mode of decay, fission yield and amounts released into the atmosphere (local fallout excluded).

B. DEPOSITS ON THE EARTH'S SURFACE

16. The Committee has traditionally estimated collective effective doses committed to the populations of the 40°-50° latitude bands in the northern and southern hemispheres (zones of maximum fallout), to the population of the whole northern hemisphere and the whole southern hemisphere, and to the entire world's population. Fission products, residual radionuclides of the weapons materials and activation products have been considered in the dose assessment.

17. The committed collective effective dose to those populations from past atmospheric testing arises mainly from external irradiation from the radionuclides deposited on the earth's surface and internal exposure from radionuclides incorporated into ingested foods. Since the doses from these pathways are strongly related to the amounts of radionuclides deposited on the ground, the first step in the dose assessment

consists in estimating the deposition densities in the latitude bands considered for the radionuclides of interest. For this purpose, the Committee has relied upon extensive measurements of ^{90}Sr, ^{89}Sr and ^{95}Zr for the assessment of the activities of all radionuclides present in the environment in a solid form. This is the case for all radionuclides considered in this Section, with the exception of ^{3}H and ^{14}C.

18. The deposition of ^{90}Sr has been monitored worldwide in a network of between 50 and 200 stations operated by and in cooperation with the Environmental Measurements Laboratory (EML), formerly the Health and Safety Laboratory (HASL) [H7]. The global deposition of ^{90}Sr has also been estimated by others, such as the United Kingdom Atomic Energy Authority [C2], with a network of 8 stations in the United Kingdom, and 18 stations elsewhere. When results of these two networks are compared, the annual values are found to differ by up to 50%, but the integrated and cumulative depositions agree to within 2% [L2]. Because the United States network has been the largest and most widely distributed, the data collected by it have been adopted by the Committee. The total hemispheric annual deposition values are calculated by averaging the deposition density over all collecting stations in each 10° latitude band, multiplying by the area of the respective band and then summing all nine bands of the hemisphere [L2].

19. Data on the time-integrated deposition of ^{90}Sr in each 10° latitude band of the globe are given in Table 2. Because the last atmospheric nuclear weapons test occurred in 1980, and deposition of radioactive aerosols takes place within a few years, it can be considered that the deposition of ^{90}Sr produced by past atmospheric tests is essentially complete. Also shown in Table 2 are the areas of the latitude bands and the population distribution in these regions. The latitudinal population distribution is used to calculate the population-weighted deposition densities, which are then used as the basis for estimating the per caput doses and dose commitments from ^{90}Sr. Owing to its rather well-known geographical distribution, ^{90}Sr is used as a fallout indicator for all long-lived radionuclides (defined here as those radionuclides with a radioactive half-life greater than 100 days) from past nuclear tests; ^{90}Sr deposition values are therefore the basic information for estimating dose commitments from a number of radionuclides. For long-lived nuclides that deposit over several years, the method of using ^{90}Sr as an indicator and applying a production ratio corrected for decay can be expected to yield adequate estimates of deposition densities. The uncertainties attached to the deposition estimates increase as the physical half-life of the radionuclide considered decreases.

20. Short-lived radionuclides (in this context, nuclides with half-lives from 8 to 100 days) show different fallout patterns. These vary not only with the half-life of the radionuclide but also with its decay chain and the chemical properties of the elements involved, because they determine the type of particles that the radionuclide will tend to be incorporated into and thus its subsequent dissemination pattern. As the deposition of all short-lived nuclides that might be of interest was not measured globally during the periods of atmospheric testing, a pattern drawn mainly from data on ^{95}Zr and ^{89}Sr has been used to infer deposition of all short-lived radionuclides [U3, U4].

21. The population-weighted deposition densities of ^{95}Zr in past tests are given in the last column of Table 2. Zirconium-95 has been chosen as the indicator for short-lived nuclides because it is a comparatively well-mapped radionuclide with a suitable half-life and it is commonly used in studies of fractionation (deviations of actual radionuclide ratios in fallout compared to what can be calculated from production yields and decay). The corresponding deposition densities of other short-lived nuclides are calculated by multiplying by an empirical factor that accounts for the difference in half-life and possible fractionation phenomena. However, the error introduced can be quite large, as the empirical factors in most cases are based on rather limited data and deposition patterns have varied among tests.

22. The ratios used to derive the population-weighted deposition densities of the radionuclides formed in atmospheric nuclear tests (based on ^{90}Sr for the long-lived radionuclides, with the exception of ^{3}H and ^{14}C, and on ^{95}Zr for the short-lived radionuclides) are presented in Table 3, along with the population-weighted average deposition densities obtained by this method for the 40°-50° latitude bands of each hemisphere, for each hemisphere and for the world.

23. This method has not been used for ^{3}H or ^{14}C, because these radionuclides are readily recycled in the biosphere and become homogeneously disseminated in the hemisphere in which they are released within a time that is short in comparison to their radioactive half-lives. The interhemispheric transfer of radionuclides other than isotopes of the inert noble gases is very limited because of tropospheric wind patterns and efficient scavenging by precipitation in the tropical latitudes. The dose commitments from ^{3}H and ^{14}C are based on a comparison with the doses and production rates of these radionuclides in their natural occurrence.

24. The quotient of the deposition density (integrated deposition density rate) to the production amount (integrated release rate) of the radionuclide forms the transfer coefficient P_{02}. These values may be

determined from the data in Tables 1 and 3. The relationship of P_{02} values to the half-lives of the radionuclides is illustrated in Figure III for the temperate zone of the northern hemisphere. Owing to the pattern of atmospheric testing, the deposition densities and thus the P_{02} values are higher by a factor of about 4 in the northern hemisphere than in the southern hemisphere. The values in the temperate zones are about 1.5 times higher than the hemispheric averages. Since the residence time of particulate debris injected into the stratosphere is of the order of one to a few years, most of the longer-lived radionuclides are deposited without appreciable decay. The P_{02} values in this case are approximately 5 kBq m^{-2} per EBq released. Radioactive decay before deposition appreciably lowers the values of P_{02} for radionuclides with half-lives of less than one year. The variations seen in Figure III of P_{02} values for a few radionuclides (^{125}Sb, ^{241}Pu) illustrate the uncertainties in production and deposition estimates.

C. TRANSFER FROM DEPOSITION TO DOSE

25. The assessments of doses from different radionuclides were presented in detail in the UNSCEAR 1977 Report [U4] and the UNSCEAR 1982 Report [U3]. Measurements reported in the scientific literature on which the estimates were based and the computational techniques applied to derive doses were listed and described. The results can be summarized in terms of the transfer coefficients P_{25}, which link the time-integrated deposition density on the earth's surface to the dose commitments in the relevant organs and tissues of man. Three principal pathways are considered: external irradiation, inhalation and ingestion.

26. The ingestion pathway is of significance for radionuclides that are efficiently transferred through the chain formed by deposition to plant uptake to grazing animals (in many cases)-dietary intake and are absorbed from the gastro-intestinal tract to blood. Some delay may be introduced in these transfers. One important exception to this, however, is the short-lived radionuclide ^{131}I, which can rather quickly be transferred via the pasture-cow-milk chain to man. For most radionuclides, the intake amounts by ingestion result primarily from the initial retention by crops and pasture during deposition and only secondarily from delayed root uptake.

27. To make reliable assessments of doses through the ingestion pathway, there is a need for extensive empirical data on the concentrations of the relevant radionuclides in different types of food and the various diets in different population groups. Analyses of this kind have been made in previous reports of the Committee, especially for ^{90}Sr and ^{137}Cs, which together with ^{14}C, are the primary contributors to the ingestion dose commitments [U3, U4]. To evaluate the P_{25} transfer coefficients, regression analysis has been applied to models relating measured radionuclide concentrations in diet to the annual deposition density rates and the measured concentrations in relevant organs.

28. The transfer of ^{90}Sr and ^{137}Cs from deposition to diet has been modelled by a three-component model:

$$C_i = b_1 \dot{F}_i + b_2 \dot{F}_{i-1} + b_3 \sum_{n=1}^{\infty} e^{-\lambda n} \dot{F}_{i-n} \qquad (2)$$

where C_i is the concentration of the radionuclide in a food component or in the total diet in the year i due to the deposition density rate in the year i, $\dot{F}_i$, in the previous year, $\dot{F}_{i-1}$, 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.

29. The transfer coefficient from deposition to diet is given by

$$P_{23} = \int_0^{\infty} C(t)\,dt \,/\, \int_0^{\infty} \dot{F}(t)\,dt$$
$$or \quad \sum_{i=1}^{\infty} C_i / \sum_{i=1}^{\infty} \dot{F}_i \qquad (3)$$

From the above model, the transfer coefficient can be expressed as

$$P_{23} = b_1 + b_2 + b_3\, e^{-\lambda m}/(1 - e^{-\lambda m}) \qquad (4)$$

where b_i are the transfer components per unit annual deposition: b_1 is the transfer in the first year, primarily from direct deposition; b_2 is the transfer in the second year from lagged use of stored foods and uptake from the surface deposit; and b_3 is the transfer via root uptake from the accumulated deposit. The units of P_{23} and b_i are Bq a kg^{-1} per Bq m^{-2}. In the exponential term, λ has units a^{-1} and m is a constant equal to one year.

30. Results of regression fitting of this fallout model to monitoring data have been presented in previous UNSCEAR Reports [U3, U4, U5]. Further analysis of the available data is presented in Table 4. The fits to the long-term monitoring results in Denmark are shown in Figure IV. Relatively minor adjustments in parameter values are needed in the fits to extended

monitoring data, indicating, in particular, that the projections of long-term transfers are confirmed.

31. Adequate representations of transfers to the total diet or to separate components of the diet are obtained for relatively uniform deposition during the year, as occurred for fallout from atmospheric weapons testing. For deposition occurring within a much shorter time period, such as following the Chernobyl accident, the transfer is dependent on the particular agricultural conditions at the time of deposition and on short-term restrictions on certain foods in the diet that may be imposed. Thus, the first-year and second-year lagged transfers of ^{137}Cs to diet in measured concentrations in 1986 and 1987 are much lower than would be expected from the fallout model. The discrepancy may have been less in other countries, depending on the agricultural conditions, than is shown for Denmark in Figure IV. In contrast to weapons fallout, the deposition of ^{90}Sr from the Chernobyl accident was much less significant than that of ^{137}Cs.

32. From the results of the transfer factor analysis given in Table 4, it is seen that transfers from widespread but relatively normal areas of transfer may vary by ±50% for total diet, with even greater variations for some specific food groups. The foods included in each major group differ in the various locations, as do the consumption amounts of these foods.

33. The transfer coefficients, P_{23}, for ^{90}Sr and ^{137}Cs are summarized in Table 5. These are the averaged results from Argentina, Denmark and the United States of the transfers to the five food categories weighted for consumption amounts. Because they come from only three locations, the average values with standard deviations are only general indications of the transfers and variations to be expected. The results are similar to the previously adopted values of P_{23}: 4 mBq a kg^{-1} per Bq m^{-2} for ^{90}Sr and 9 mBq a kg^{-1} per Bq m^{-2} for ^{137}Cs [U3].

34. Figure V shows the contributions to transfer in the various periods. For ^{90}Sr, the major component of P_{23} (50%) arises from transfer from the deposit. For ^{137}Cs, the major transfer is within the first year of deposition (45%), with diminishing transfer in the second and subsequent years following deposition. The contributions to transfers by the various food groups are indicated in Table 5. For ^{90}Sr, milk and grain products are the most significant foods. For ^{137}Cs, these categories, along with meat, account for the major part of the transfer. It is recognized that much wider variations in transfer occur in certain areas for particular soil conditions and foods. This includes the Arctic food chain (lichen-reindeer-man) and areas where the caesium-binding clay content of soils is low, thus allowing higher and more persistent uptake of ^{137}Cs to plants. In these cases, order of magnitude differences in transfer may result. More detailed evaluations of the extent of these conditions are necessary to determine the added contributions that may be made to the collective doses.

35. The transfer coefficients P_{34}, linking concentrations of radionuclides in diet to those in the body and P_{45}, linking concentrations in the body to dose, have been evaluated and the results published in the UNSCEAR 1982 Report [U3] and the UNSCEAR 1977 Report [U4]. For some radionuclides, the integrated dietary intake rates have been determined directly. Relating these values to the deposition of the radionuclide forms the transfer coefficient P_{24}. The units of this expression are Bq per Bq m^{-2}. Values of P_{23} may be transformed to this by multiplication by the consumption rate of foods, which is in effect the transfer coefficient P_{34}. As this is a convenient form for estimating dose, all radionuclides considered in the ingestion pathway evaluation are included in the listing of P_{24} values in Table 6.

36. The values of the dose per unit intake of radionuclides are, in fact, the transfer coefficients P_{45}. These have been or are being re-evaluated, based on the latest metabolic data, and compilations are available [I13, N1]. It is necessary to state the specific assumptions of absorption and retention of the radionuclides; therefore, the P_{45} values used in the evaluations given here are included in Table 7. The values of effective dose use the weighting factors defined by the ICRP in 1990 [I12].

37. The overall transfer coefficients P_{25}, linking the deposition to the dose from radionuclides produced in atmospheric nuclear testing, are compiled in Table 8. The results for the ingestion pathway have been obtained by multiplication of the transfer coefficients P_{24} in Table 6 and P_{45} in Table 7. The values of P_{25} are considered to apply as averages to large populations in the world. Adjustments are needed if applications are to be made to smaller groups for which diet or local conditions of transfer may be different.

38. For the inhalation pathway, the association is between atmospheric concentrations and dose, P_{15}, but because there is a direct relationship between atmospheric concentration and deposition, the association with dose from inhalation can also be made from the deposition amount. The expression used is

$$P_{25} = P_{14} P_{45} / P_{12} \qquad (5)$$

where P_{14} is the average breathing rate of the individual in the population, P_{45} is the dose per unit

intake factor for the organ or tissue considered and P_{12} is the deposition velocity averaged over all weather conditions, including precipitation. The value of P_{14} has been taken to be 20 m^3 d^{-1}, or 7,300 m^3 a^{-1} for all populations. The values of P_{45}, in nGy Bq^{-1}, are listed in Table 7. The transfer coefficient P_{12} varies with the precipitation rate at various locations and also with the physical and chemical nature of the radionuclide considered. The average value of P_{12} for particulate material has been estimated to be 1.76 cm s^{-1}, or 5.56 10^5 m a^{-1}. Although this value is based on observations in New York City over several years [B5], measurements in the United Kingdom [C3] and Sweden [B6, D1] are in reasonable agreement, after normalization to the same annual precipitation. Furthermore, since the yearly rainfall in New York City is fairly close to the population-weighted average for the whole world, the New York value is considered adequate for global average calculations. The transfer coefficients P_{25} evaluated for the inhalation pathway are listed in Table 8.

39. In addition to experiencing internal irradiation from inhaled or ingested radionuclides, people are also irradiated externally from gamma-emitting nuclides dispersed in the air and deposited on the ground. As the debris normally spends much more time deposited on the ground than dispersed in ground-level air, the external dose due to irradiation from the earth's surface is normally much higher than the dose due to irradiation while the debris is airborne. The average ratio of the absorbed dose from ground surface contamination to that from air immersion is proportional to the half-life of the radionuclide and is, for example, of the order of 100 for short-lived ^{140}Ba and 1,000,000 for long-lived ^{137}Cs.

40. The P_{25} transfer coefficients for external irradiation have been calculated by multiplying the dose rate conversion factors for radionuclides deposited on the ground, derived from Beck [B3], by the mean lifetime of the radionuclide (half-life ÷ ln 2) and by an average factor assuming 80% indoor occupancy in buildings with a shielding factor of 0.2. The latter factor is 0.7 Sv per Gy (equivalent dose rate in the body per unit absorbed dose rate in air) times 0.36 (0.2 outdoor occupancy plus 0.8 indoor occupancy times 0.2 building shielding). The Committee has in the past [U3, U4] rounded this product to 0.3; the procedure here, however, is to postpone the rounding to the final dose estimate. For short-lived radionuclides (all except ^{137}Cs), the dose-rate conversion factor applying to a plane source is used. For ^{137}Cs, the dose-rate conversion factor applying to an exponential concentration profile in the ground of mean depth 3 cm is used. The indoor occupancy, as well as the shielding factor, varies a great deal among different populations of the world, and this is a source of uncertainty in the dose assessments for external irradiation. Also, the different dynamic behaviours of radionuclides deposited in urban and in rural environments have not been taken into account for the dose estimates from radionuclides produced in atmospheric nuclear testing. The transfer coefficients P_{25} are given in Table 8 for the effective dose commitment. The same numerical values can be expected to apply more or less to the absorbed doses in individual organs in the body; however, since the absorbed doses per unit deposition density have not been specifically evaluated, there are no values given in Table 8.

D. DOSE ESTIMATES

1. Regional and global exposure

41. The effective dose commitments from individual radionuclides in past atmospheric testing (^3H and ^{14}C excepted) can be calculated by multiplying the population-weighted integrated deposition density of the radionuclide in the region of interest (Table 3) by the appropriate P_{25} transfer coefficient (Table 8). As an example, the effective dose commitment due to ingestion of ^{137}Cs in the population of the 40°-50° latitude band in the temperate zone of the northern hemisphere is 5,200 Bq m^{-2} times 54.6 nSv per Bq m^{-2} = 280 μSv. The results for each radionuclide and for all pathways are given in Table 9.

42. As indicated previously, the dose commitments from ^3H and ^{14}C are derived from comparisons with the natural doses and production rates by cosmic rays. The dose calculations make use of the fact that the dose commitment to production ratios for those radionuclides are equal to the annual natural dose to production ratios. The annual absorbed dose in tissue from natural tritium has been estimated to be 10 nGy, resulting from an annual production per hemisphere of 37 PBq [U3]. Assuming a total release from atmospheric nuclear testing of 190 EBq to the atmosphere of the northern hemisphere and 50 EBq to that of the southern hemisphere [U3], the absorbed dose commitments in tissue from fallout tritium are as follows: northern hemisphere, 1.9 10^{20} Bq × (10^{-8} Gy a^{-1}) ÷ (3.7 10^{16} Bq a^{-1}) = 51 μGy, and southern hemisphere, 0.5 10^{20} Bq × (10^{-8} Gy a^{-1}) ÷ (3.7 10^{16} Bq a^{-1}) = 14 μGy. It has not been possible to account for latitudinal variations in the tritium distribution. The simplification is made in assuming fairly rapid mixing of tritium throughout the hemisphere. The effective dose commitments from ^3H are 51 μSv (northern hemisphere), 14 μSv (southern hemisphere) and 47 μSv (world). The global value is the population-weighted estimate, taking into account that 89% of the world population resides in the northern

hemisphere and 11% in the southern hemisphere. On the basis of the intake rates of hydrogen in water [N8], the dose commitment can be apportioned as 7% arising from inhalation and absorption through the skin and 93% from ingestion [U3].

43. Carbon-14 is produced naturally by cosmic ray neutrons impinging on nitrogen in the upper atmosphere. This means that the dose commitment from ^{14}C injected into the atmosphere by nuclear tests can be calculated in the same way as the dose commitment from tritium produced in atmospheric tests. The annual natural production of ^{14}C of about 1 PBq and the resulting equilibrium specific activity in man yields an annual dose to the gonads of 5 μGy [U3]. Based on this, it can be concluded that the 220 PBq from nuclear explosions have given a dose commitment to the gonads of all populations of (5 μGy a^{-1}) ÷ (1 PBq a^{-1}) x 220 PBq = 1,100 μGy. In the same way, dose commitments to the lungs, bone lining cells, red bone marrow, thyroid and other tissues can be assessed as 1,300, 4,800, 5,300, 1,300 and 2,900 μGy, respectively [U3], yielding an effective dose commitment of 2,600 μSv. The corresponding collective effective dose per unit release is 120 man Sv per TBq, assuming an equilibrium world population of 10^{10} people reached in the next century and maintained over the next thousands of years. Other published estimates range between 67 and 159 man Sv per TBq [B10, I2, K2, K4, K5, M2, S1].

44. The ^{14}C doses are due to ingested and inhaled carbon. On the basis of the relative intake and retention of carbon in these pathways, the dose commitments from ingestion are estimated to be 10^4 times larger than those arising from inhalation [K4]. The dose commitments from ^{14}C are delivered over a very long time period. From calculations based on an environmental compartment model for ^{14}C that comprises 25 discrete carbon reservoirs (Figure VI) and takes into account the dilution of ^{14}C by stable carbon released during fossil fuel combustion, it is estimated that only 5% of the dose commitment is delivered in the first 100 years after the release of ^{14}C; about 71% of the dose commitment will have been delivered during 10^4 years after the release of ^{14}C [M2]. The deep ocean, divided into 18 compartments, accounts for the slow recycling of ^{14}C into the biosphere.

45. The effective dose commitments from atmospheric nuclear testing for all of the 22 radionuclides considered for the populations of the world and of the 40°-50° latitude bands of each hemisphere are presented in Table 9. The total effective dose commitments are 4.4 and 3.1 mSv in the 40°-50° latitude bands of the northern and southern hemispheres, respectively, and the global average is 3.7 mSv.

46. The summary listing in Table 10 for the world population shows that ^{14}C is the dominant contributor to the total effective dose commitment, accounting for 70% of the effective dose commitment to the world's population. However, if only 10% of the ^{14}C dose commitment is included in the comparison, that is, if the dose commitments are truncated approximately to the year 2200, at which time all other radionuclides will have delivered almost all of their dose, ^{14}C contributes only 19% to the truncated effective dose commitment to the world's population. Besides ^{14}C, the most important contributors to the effective dose commitment to the world population are ^{137}Cs, ^{95}Zr-^{95}Nb, ^{90}Sr, ^{106}Ru, ^{54}Mn, ^{144}Ce, ^{131}I and ^{3}H.

47. Including all of the ^{14}C dose, 16% of the total effective dose commitment to the world population is delivered through external irradiation, 4% through inhalation and 80% through ingestion. Including only 10% of the ^{14}C dose, the corresponding numbers are 44%, 10% and 46%, respectively. Thus, ingestion is the most important pathway, if ^{14}C is fully included, while ingestion and external irradiation are about equally important, if only 10% of effective dose commitment from ^{14}C is included. In both cases inhalation contributes substantially less.

48. As the explosive power in past atmospheric tests has been estimated to be 545 Mt, it may be concluded that the past tests have given an average complete effective dose commitment of about 7 μSv Mt^{-1} to the world population. Of this, about 5 μSv Mt^{-1} is due to ^{14}C and about 2 μSv Mt^{-1} to fission products. The transuranium elements have contributed about 0.1 μSv Mt^{-1}. Normalizing the fission product dose commitment to the total fission yield exploded of 217 Mt gives an estimate of about 5 μSv Mt^{-1} fission.

49. A summary of the global collective effective doses committed from past atmospheric nuclear tests is given in Table 11. For these calculations, some assumptions about the global population have been made. For inhalation exposure and other exposures from radionuclides with half-lives of less than a few years, the population of the world has been taken to be 3.2 10^9 persons, as it was in the early 1960s during maximum fallout. For ^{3}H, ^{90}Sr, ^{137}Cs and ^{241}Pu, a global population of 4 10^9 persons has been applied, and for the very long-lived ^{14}C, ^{239}Pu, ^{240}Pu and ^{241}Am, the projected global population has been assumed to be 1 10^{10} persons.

50. In Table 11 the radionuclides are listed in order of their decreasing contributions to the collective effective dose. The order is essentially the same as in Table 10, with ^{14}C being the dominant contributor and ^{137}Cs, ^{90}Sr, ^{95}Zr and ^{106}Ru following. The total global

impact of all atmospheric nuclear explosions carried out for test purposes in the past is 3 10^7 man Sv.

2. Local exposure

51. Populations living near the sites where nuclear weapons tests took place received relatively higher doses than the average values assessed above. In the United States, about 100 surface or near-surface tests were conducted at the Nevada test site between 1951 and 1962, with a total explosive fission yield of approximately 1 Mt. Dose reconstructions have been undertaken for the populations living in the vicinity of the Nevada test site during the period of atmospheric testing [C7, W1]. The local population size was 180,000 persons. Preliminary results indicate that thyroid doses of up to 1 Gy may have been received by children. The collective dose from external exposure has been estimated to be approximately 500 man Sv [A5]. Ninety per cent of the collective dose was received during the years 1953-1957.

52. Following the nuclear test Bravo at Bikini in the Pacific test site of the United States, residents of Rongelap and Utirik Atolls were exposed to unexpected fallout. The islands are 210 and 570 km, respectively, east of Bikini. Eighty-two individuals were evacuated from Rongelap 51 hours after the explosion and 159 persons were removed from Utirik within 78 hours. External exposures, mainly from short-lived radionuclides, ranged from 1.9 Sv on Rongelap (67 persons, including 3 in utero), 1.1 Sv on nearby Allingnae Atoll (19 persons, including 1 in utero) and 0.1 Sv on Utirik (167 persons, including 8 in utero) [L3]. The collective dose was thus of the order of 160 man Sv. Doses to the thyroid, caused by several isotopes of iodine, tellurium and by external gamma radiation, were estimated to be 12, 22 and 52 Gy on average and 42, 82 and 200 Gy maximum to adults and children of 9 years and 1 year, respectively, on Rongelap [L3].

53. At the Semipalatinsk test site in the Kazakh region of the former USSR, atmospheric tests were conducted from 1949 through 1962, and about 300 underground tests were conducted from 1964 until 1989 [T5]. In total, 10,000 people in settlements bordering the testing site were exposed to some extent. The collective dose due to external irradiation was estimated to be 2,600 man Sv, 80% of which resulting from testing in the period 1949-1953, due to external irradiation and 2,000 man Sv due to internal exposure from the ingestion intake of radionuclides [T5]. The collective absorbed dose to the thyroid was of the order of 10,000 man Gy.

54. The United Kingdom conducted a programme of nuclear warhead development tests between 1953 and 1963 in Australia, at the Monte Bello Islands and at Emu and Maralinga on the mainland. In all, twelve major nuclear tests involving atomic explosions with total yields of about 100 kt, 16 kt and 60 kt were performed at the three sites, respectively [D3]. The collective effective dose to the Australian population from these test series has been estimated to be 700 man Sv [W3]. In addition, several hundred smaller scale experiments were performed at Maralinga [D3] which resulted in the dispersal of about 24 kg of ^{239}Pu over some hundreds of square kilometres. This area remains contaminated and potential doses to future inhabitants of the Maralinga and Emu areas have been assessed with a view to rehabilitation of the two sites [D3, H3, W2]. Annual effective doses of several millisievert would be expected to result from continuous occupancy within the two areas, with maximums of several hundred millisievert in the immediate vicinity of the two sites.

II. UNDERGROUND NUCLEAR TESTS

55. About 1,400 nuclear test explosions have been carried out beneath the earth's surface. Particularly since 1963, when the limited nuclear test ban treaty banning atmospheric tests was agreed, the practice became more frequent. Prohibiting atmospheric tests was a crucial step in lessening the doses to the world's population from tests of weapons. In fact, a well-contained under-ground nuclear explosion delivers extremely low doses or dose commitments to any group of people. However, there have been occasions when, owing to venting or the diffusion of gases, radioactive materials leaked from underground tests, resulting in the dissemination of radioactive debris over at least regional distances.

A. WEAPONS TESTS

56. Estimates of annual yields and numbers of underground tests have been compiled from data collected by the National Defence Research Establishment in Sweden [N10]. The total annual yields are

presented in Table 12. The basis for these estimates are either announcements made by the testing nation or simple calculations employing a formula of the following form:

$$\text{yield (kt)} = 10^{(M-a)/b} \qquad (6)$$

where M stands for the seismic surface or body wave magnitude and a and b are constants that vary with wave type, explosion location and observing laboratory. The total yield of underground tests is estimated to be 90 Mt, or about one sixth of the total yield exploded in the atmosphere.

57. More than 500 tests were conducted underground at the Nevada test site in the United States, but only 32 are reported to have led to off-site contamination as a result of venting [H4]. Table 13 shows, as an example, the atmospheric releases of ^{131}I from these 32 underground tests. The total amount of ^{131}I released into the atmosphere was about 5 PBq, which is five orders of magnitude smaller than the amount produced by atmospheric testing ($6.5\ 10^5$ PBq, from Table 1). The amount of ^{131}I or of any other radionuclide released into the atmosphere by underground tests carried out at sites other than the Nevada test site is not available.

58. The collective effective dose per unit release of ^{131}I would be expected to be much greater for the venting of underground tests than for atmospheric tests, because the release from underground tests occurs at ground level instead of higher in the atmosphere. Estimates of collective effective dose per unit release to the lower layers of the atmosphere were made in the UNSCEAR 1988 Report [U1]; these estimates are $1\ 10^{-13}$ man Sv per Bq for ^{131}I released in the Chernobyl accident and $4\ 10^{-13}$ man Sv per Bq for ^{131}I released from nuclear power stations. In order to account for the low population densities in the vicinity of weapons tests sites, it is assumed that a lower figure, $1\ 10^{-14}$ man Sv per Bq, is appropriate for releases of ^{131}I from underground tests. This figure, combined with a release of 5 PBq, leads to a collective effective dose from ^{131}I releases from venting underground tests carried out at the Nevada test site of 50 man Sv. Extrapolating to the total number of underground tests (1,400) at all locations would indicate that 15 PBq, in total, of ^{131}I has been released, and the collective dose is of the order of 150 man Sv. In comparison, the corresponding collective effective dose from ^{131}I from past atmospheric tests is estimated to be 164,000 man Sv (Table 11).

59. Other than these rather unusual events, where amounts of radioactive materials have been collected on filters, it is reasonable to assume that a few high-yield underground tests have leaked radioactive gases such as tritium or noble gases such as ^{133}Xe. There have been suggestions that observed peak concentrations in atmospheric tritium (HT or HTO) and ^{37}Ar (produced in $^{40}Ca(n,\alpha)^{37}Ar$ reactions underground) could have been due to leakages from underground explosions [B7, L5, M1]. Traces of short-lived radionuclides resulting from tests in the USSR were observed in Finland and Sweden in 1966 [K1, P2] and in 1971 [E1, K6]. The collective dose to the population of Sweden was estimated to be 3 man Sv from the venting of an underground test at Semipalatinsk in 1966 and 0.1 man Sv or less on seven other occasions when radionuclides from underground tests were detected in that country [D10].

60. The total ^{131}I produced in the underground explosions could be estimated to be 90 Mt total yield times the normalized fission production of 4,200 PBq Mt^{-1} (Table 1), which is 380 EBq. The fractional release is thus $4\ 10^{-5}$ of the amount produced. This same estimate of the release fraction may be applied to the noble gases, of which ^{133}Xe is the predominant radionuclide. The normalized fission production of ^{133}Xe is 14.5 EBq Mt^{-1} (6.54% fission yield [R1], adjusted for the half-life and yield of ^{90}Sr production given in Table 1). Total production of ^{133}Xe in underground tests is then estimated to be 1,300 EBq, of which 50 PBq may have been released (90 Mt × 14.5 EBq Mt^{-1} × $4\ 10^{-5}$). The normalized collective dose from noble gases estimated for surface releases (applied to releases from nuclear power reactors) is 0.1 man Sv PBq^{-1} [U1]. The collective dose due to noble gases released from underground tests is then 50 PBq × 0.1 man Sv PBq^{-1} = 5 man Sv. This estimate is very uncertain. The collective dose per unit release may be overestimated because of the remote locations of the test sites; however, there is even greater uncertainty in the release fraction.

61. The same estimation procedures applied to ^{3}H produced in underground testing would indicate a total release of 10^{-4} PBq and a collective dose of 0.001 man Sv. This is a negligible component of the collective dose under the assumptions made. The analysis indicates that releases of ^{131}I are of the most significance and that the total collective dose from released radioactive materials from the 1,400 underground tests conducted thus far is of the order of 200 man Sv. Evaluations have not yet been made of potential exposures resulting from residual debris underground at the sites of the explosions.

B. PEACEFUL NUCLEAR EXPLOSIONS

62. It is to be expected that shallow underground explosions conducted for excavation purposes or deeper underground explosions in mining operations

also involve releases of radioactive materials to the environment. Programmes to develop applications of peaceful nuclear explosions were carried out during the 1960s in the United States and USSR. About 100 test explosions were performed. The presumed advantages of nuclear explosions have, however, been outweighed by the residual contamination and other disadvantages.

63. Doses to local or global populations from peaceful nuclear explosions have resulted primarily from cratering experiments. There were 6 such tests at the Nevada Test Site between 1962 and 1968 and a reported 9 experiments worldwide [U5]. The collective dose to the local population (180,000 persons) living near the Nevada site has been estimated to be 3 man Sv from the Sedan 104 kt cratering experiment in 1962 [A5]. The total from all tests, peaceful and military, conducted at the Nevada site from 1961 to 1975 was 5.7 man Sv [A5]. Therefore the total local collective dose from peaceful nuclear explosions can be estimated to be no more than 5 man Sv at Nevada and perhaps 10 man Sv worldwide.

64. The long-range dose commitment from the Schooner cratering experiment in the United States in 1968 was estimated in the UNSCEAR 1972 Report [U5]. Tungsten-181, formed in the neutron shield used to minimize the formation of activation products, was detected in several locations in Europe after this event. The effective dose commitment was estimated to be 12 nSv from radionuclides other than ^{3}H in the population of the 40°-50° latitude band of the northern hemisphere (630 million persons at the time) [U5]. The estimated release of ^{3}H of 15 PBq [U5] would have resulted in a dose commitment of 4 nSv (0.27 nGy PBq^{-1} from comparison with natural ^{3}H dose and release in the northern hemisphere) in the population of the northern hemisphere (3,160 million persons at the time). The collective dose from this test is thus estimated to be 20 man Sv. If it may be considered that this result is representative of the other cratering experiments, the collective dose worldwide from cratering experiments is 180 man Sv. The collective dose from peaceful nuclear explosions is thus estimated to be the same order of magnitude as that from venting underground military tests.

III. NUCLEAR WEAPONS FABRICATION

65. The production of radioactive materials for military use and the fabrication of weapons has involved routine and accidental releases of radionuclides and exposures of local or regional populations. These dose commitments and collective doses have not been estimated before by the Committee because no data were available. Some of the secrecy of this industry is being reduced, however, and information on discharges and doses from recent (and, in some cases earlier) operations is being provided. With this information and some rough estimates of the total amounts of radioactive materials produced, the doses from the weapons industry can be estimated.

66. The radioactive components of nuclear weapons are the fissile nuclides ^{239}Pu and ^{235}U; the fertile nuclide ^{238}U, which fissions only if irradiated by high-energy neutrons; tritium; and in some presumably older constructions small amounts of materials such as ^{210}Po, which are used to initiate the chain reaction in the fission bomb. Tritium is used in boosted fission bombs, where the efficiency is increased by neutrons from a comparatively small thermonuclear reaction fuelled by tritium. Tritium is probably also used in the main thermonuclear stage of some types of hydrogen bombs.

67. Doses arise in several stages of the nuclear weapons production line. As in the nuclear energy fuel cycle, production starts with the mining and milling of uranium. After that there is the need to convert the uranium to uranium hexafluoride gas, which is the form of uranium used at the gas diffusion or centrifugation plant where the ^{235}U content is enriched. If this process is carried to enrichments of the order of 90%, weapons-grade uranium is produced, which can be used directly to fabricate nuclear weapons components. Alternatively, the enrichment can be omitted or carried to only a few per cent. The uranium is then used to fuel reactors, which coupled to reprocessing and purification yields plutonium and tritium for the weapons. Some doses also derive from the weapons fabrication and assembly, as well as from the maintenance, transportation and recycling of weapons. Doses resulting from routine releases are considered in this Chapter.

A. PRODUCTION AMOUNTS

68. The total amounts of radioactive materials produced for weapons use are not known from directly reported information. An assessment has been made of plutonium in present weapons stockpiles by consider-

ing the amounts of long-lived fission products in high-level waste in the United States and by analysing the global atmospheric inventory of ^{85}Kr [H5]. Krypton-85 is a noble gas and a long-lived fission product that is released to the atmosphere when reactor fuel is reprocessed, for example, to extract plutonium. Correcting the global inventory mainly for the hitherto modest civilian reprocessing yields a number that may be seen to be a measure of the global plutonium stockpile. The estimated stockpiles in the United States and the former USSR were estimated to be around 100 tonnes in each country.

69. According to United Nations studies in 1981 and 1990 on nuclear weapons, the nuclear arsenals comprise more than 40,000 weapons with a total explosive yield of 13,000 Mt [U11, U12]. If it is assumed that the first fission stage in all these weapons is based on plutonium, a total inventory of weapons plutonium of 200 tonnes implies that, on average, 5 kg is used in each device. This is a reasonable figure [E5], which thus lends some credibility to the estimated total production.

70. Tritium is also produced for weapons use. It decays with a half-life of 12.32 years, which means that tritium must be produced continually to preserve the weapons stockpile. It has been estimated for the United States that an annual production of 3 kg of tritium is just enough to balance the decay [C11], and from this the total amount of tritium in the United States stockpile can be easily calculated to be about 55 kg. The world tritium stockpile can then be assumed to be twice as much, or around 110 kg. If it is assumed that this tritium was first produced in the early 1960s and has been maintained since then, a total tritium production of 110 + 30 × 6 = 290 kg results. If a further reasonable assumption is made, that is, that tritium is produced at the same (atom)rate as plutonium in the reactor, these 0.29 tonnes of tritium are equivalent to a production of (239/3) 0.29 = 23 tonnes of plutonium.

B. RELEASES AND DOSE ESTIMATES

71. In the United States, weapons production activities have been centred at locations reporting mainly through four regional offices of the Department of Energy: Albuquerque, Oak Ridge, Richland and Savannah River. Doses reported from these centres between 1976 and 1982 are considered to contribute about 90% of the population dose from activities related to weapons research and production. Little information is available on doses or releases before 1976. Efforts are being made, however, to reconstruct doses to the public living near nuclear installations, and some data from earlier periods are becoming available.

72. The Hanford nuclear weapons facility in the United States released substantial quantities of radioactive materials into the atmosphere and the Columbia River from its plutonium production reactors and fuel reprocessing facilities. Two plutonium production reactors started operating at Hanford in December 1944. Two fuel reprocessing plants began extracting plutonium in the same month, and a third production reactor was added in 1945 [C5]. The atmospheric releases of ^{131}I from reprocessing facilities were estimated from the quantity of reactor fuel reprocessed and the time interval between removal from the reactors and reprocessing. Table 14 presents the estimated annual releases of ^{131}I into the atmosphere from 1944 to 1956 [C5]. The largest releases of ^{131}I occurred between 1944 and 1946 during the effort to develop and produce the first arsenal of nuclear weapons. At that time, fuel rods were reprocessed soon after their removal from the reactors in order to maximize plutonium production, and there was no filtering or chemical processing of ^{131}I before atmospheric release. About 18 PBq of ^{131}I was released into the atmosphere between 1944 and 1946, while the release from 1947 to 1956 amounted to about 2 PBq (Table 14). The total atmospheric release of ^{131}I was 20 PBq between 1944 and 1956. Preliminary calculations indicate that the maximum thyroid doses were of the order of 10 Gy in 1945 [C5]. The collective effective doses, based on a value of 4 10^{-13} man Sv per Bq of ^{131}I released from nuclear installations and a population density of 25 persons per km^2 [U1, W4], are roughly estimated to be 7,000 man Sv for 1944-1946 and 1,000 man Sv for 1947-1956. These figures do not include the contributions from other radionuclides in the airborne discharges, which have not yet been reported, or from the liquid releases to the Columbia River. The dose reconstruction effort, which is scheduled to be finished in 1994, will produce more complete and accurate dose estimates.

73. The Chelyabinsk-40 centre, located near the town of Kyshtym, was the first Soviet nuclear installation dedicated to the production of plutonium for military purposes. A uranium-graphite reactor with an open cooling water system was commissioned in June 1948, and a fuel reprocessing plant started operating in December 1948 [N5]. Liquid releases to the Techa River from 1949 to 1956 amounted to 100 PBq, with 95% of this release being discharged from March 1950 to November 1951 [K7]. The main contributors to the activity associated with the radioactive materials released were ^{89}Sr (8.8%), ^{90}Sr (11.6%), ^{137}Cs (12.2%), rare-earth isotopes (26.8%), ^{95}Zr-^{95}Nb (13.6%) and ruthenium isotopes (25.9%) [K7]. These

large releases appear to have resulted in large part from a lack of waste treatment capability and from the storage of radioactive wastes in open, unlined earthen reservoirs [T4]. A hydrological isolation system, including a small reservoir called Lake Karachay, was built after 1952 to contain the low- and intermediate-level wastes.

74. The population along the Techa River was exposed to both external and internal irradiation. External irradiation was caused by gamma radiation from ^{137}Cs, ^{106}Ru and ^{95}Zr in the flood-plain areas, in vegetable gardens near the houses, and inside the houses. Internal irradiation was mainly due to the consumption of water and of local foodstuffs contaminated with ^{89}Sr, ^{90}Sr, ^{137}Cs and some other radionuclides. Tissue and effective doses, presented in Table 15, have been estimated for the populations living along the 240-km-long Techa River [A4]. Average cumulative effective doses are estimated to have ranged up to 1,400 mSv in the village of Metlino, located 7 km downstream from the point of discharge. The evacuation of the population of that village started in 1953; from 1955 to 1960, inhabitants of another 19 settlements were moved away from the river. Altogether, 7,500 persons were evacuated [K7]. It appears from Table 15 that all villages along the Techa River within about 50 km of the plutonium production centre were evacuated. The collective effective dose can be assessed from the distribution of estimated cumulative effective doses to individuals, which are as follows [A4]: 0-50 mSv, 10% of population; 50-100 mSv, 44%; 100-200 mSv, 18%; 200-250 mSv, 15%; 250-500 mSv, 2%; 500-1,000 mSv, 3%; and >1,000 mSv, 8%. Assuming that the 11% of the exposed population who received cumulative effective doses greater than 500 mSv is identical with the 7,500 persons who were evacuated, the collective effective dose received by the population living along the Techa River is about 15,000 man Sv. This value does not include the contributions from the airborne discharges, which have not been reported, or from the contamination of the Iset River, into which the Techa River discharges its waters.

75. These data from Hanford and Chelyabinsk give some indications of doses from the earlier practice of nuclear weapons fabrication, but it is difficult to extrapolate this information to the total weapons industry. Another method of estimating dose is to relate the radioactive material production amounts to the doses involved in producing and utilizing nuclear fuels in the civilian fuel cycle. Plutonium production reactors, which are optimized for the purpose, produce about 1 g of ^{239}Pu per MW d (thermal power), which, if a thermal conversion of 0.33 is assumed, can be expressed, for comparison, as 1.1 tonne per GW a of electrical power. This means that the plutonium and tritium in present arsenals correspond to (200 + 23)/1.1 = about 200 GW a (electrical power) of reactor operation. According to the UNSCEAR 1988 Report [U1], 1 GW a of electrical power in the civilian fuel cycle yields a collective dose of 4 man Sv locally and regionally and 200 man Sv globally. The total collective effective dose committed from weapons plutonium and tritium production may thus be estimated to be 800 man Sv locally and regionally and 40,000 man Sv globally.

76. The estimated annual collective doses from weapons production activities in the United States, as reflected in reports of the Department of Energy for the four main locations between 1976 and 1982, were 5.8, 8.2, 5.2, 2.2, 2.4, 2.3 and 1.7 man Sv, respectively [D7]. The United States nuclear weapons stockpile grew by the mid-1960s to somewhat above 30,000 weapons [C12]. Since then, as older weapons have been retired, the stockpile has decreased, to some 25,000 weapons. However, some of the retired weapons have been replaced, and tritium has been produced continually to balance the radioactive decay. From the reported variation with time of the annual doses since 1976, it can be assumed that the collective dose per year of practice increases as one goes back in time. Assuming that the mean annual population dose commitment from 1965 to 1990 was 10 man Sv and that during this period, on average, 1,000 weapons were produced annually, an average population dose commitment of 0.01 man Sv for each weapon produced is estimated. With a total United States production of 30,000 + (20 × 1,000) = 50,000 weapons, the total estimate would be 500 man Sv. With similar doses from weapons production in the Soviet Union, the collective dose committed to the local and regional population from nuclear weapons production in the world would become 1,000 man Sv, in agreement with the estimate based on plutonium and tritium production in the previous paragraph.

77. This estimate of about 1,000 man Sv for the local and regional collective dose from the global nuclear weapons industry in more recent practice is admittedly uncertain, as it is based on many assumptions and few data. The global component of the collective effective dose is also rather uncertain, as it mainly arises from radon releases from mill tailings in the next 10^4 years. The amounts of enriched uranium produced for weapons purposes are not known, and this part of the military fuel cycle has not yet been assessed. However, even if the committed collective dose from nuclear weapons research, development and production is taken to be roughly 100,000 man Sv, this represents less than 1% of the committed collective dose from atmospheric testing, which according to Table 11 was about 3 10^7 man Sv.

IV. NUCLEAR POWER PRODUCTION

78. The generation of electrical energy by nuclear reactors has continually increased since the beginning of this practice in the 1950s. In 1989, the electrical energy generated by nuclear reactors amounted to 212 GW a, representing 17% of the world's electrical energy generated in that year and 5% of the world's energy consumption [I7].

79. The nuclear fuel cycle includes the mining and milling of uranium ore, its conversion to nuclear fuel material, which usually includes the enrichment of the isotopic content of ^{235}U, the fabrication of fuel elements, the production of energy in the nuclear reactor, the storage of irradiated fuel or its reprocessing with the recycling of the fissile and fertile materials recovered, and the storage and disposal of radioactive wastes. Radioactive materials are transported between installations in the entire fuel cycle.

80. Radiation exposures of members of the public resulting from effluent discharges of radioactive materials from installations of the nuclear fuel cycle were assessed in previous UNSCEAR Reports [U1, U3, U4, U5], in which discharge data for 1970-1974, 1975-1979 and 1980-1984 were included. In this Annex, similar data are presented for the years 1985-1989, as well as the trend with time of the normalized annual releases since 1970. The doses are estimated using the same environmental and dosimetric models as in the UNSCEAR 1988 Report [U1]. In this Chapter doses to the public from routine effluent discharges are considered.

81. The doses to the exposed individuals vary widely from installation to installation and from one location to another, and the individual dose generally decreases rapidly with distance from a given source. In this Annex, an indication is given of the range of individual doses associated with each type of installation. To evaluate the total impact of radionuclides released at each stage of the nuclear fuel cycle, results are normalized in terms of the collective effective dose per unit quantity of electrical energy produced, expressed as man Sv per GW a. The estimated amounts of natural uranium, uranium oxide (U_3O_8), fuel, and units of enrichment required to generate 1 GW a of electrical energy are presented in Table 16 for several reactor types [O2, O3].

A. MINING AND MILLING

82. Uranium mining operations involve the removal from the ground of large quantities of ore containing uranium and its decay products at concentrations of between a tenth of a per cent and a few per cent. In comparison, the average concentrations of uranium in soils of normal natural background areas are of the order of 1 ppm. Uranium is mined using underground or open-pit techniques. The annual quantities of uranium produced in 1975-1989 are presented in Table 17 [O2]. The total amount of uranium produced worldwide remained fairly stable between 1985 and 1990, at about 50,000 tonnes, extracted from about 20 million tonnes of ore. Milling operations involve the processing of these large quantities of ore to extract the uranium in a partially refined form, known as yellow cake.

1. Effluents

83. Radon is the most important radionuclide released from uranium mines. Data on radon emissions from mines in Australia, Canada and the German Democratic Republic for the period 1985-1989 are collected in Table 18. Releases normalized to the production of uranium oxide (U_3O_8) ranged from 1 to 2,000 GBq t^{-1} and were, for most mines, much greater in Canada and in the German Democratic Republic than in Australia. The production-weighted average of the normalized radon release is 300 GBq t^{-1} of uranium oxide. Since about 250 t uranium oxide are required to produce 1 GW a of electrical energy (Table 16), the average radon release, normalized to the generation of electri-cal energy, is approximately 75 TBq $(GW\ a)^{-1}$. This is greater, by a factor of almost 4, than the value adopted in the UNSCEAR 1982 Report and the UNSCEAR 1988 Report. Previous data have been both limited and variable. The present database is somewhat more extensive, and a production-weighted average has been calculated.

84. Releases of natural radionuclides in uranium milling have been reported for mills in Australia and Canada. Results for airborne releases are shown in Table 19. The releases normalized to electrical energy generated are comparable to values adopted in the UNSCEAR 1982 Report and the UNSCEAR 1988 Report. Some variability is inherent, given the limited data available. Mill sites in dry areas give rise to effectively no liquid effluents. The run-off water of mills in wet climates, however, will contain radionuclides and may need treatment before release into watercourses. Liquid releases have been reported for two Canadian uranium mills and are presented in Table 20. There is no obvious explanation for the relatively large amounts of uranium in releases, compared to the other radionuclides of that decay series.

85. The extraction of uranium during milling is made as complete as possible but cannot reach 100%. Typically, the residual tailings from the mill will contain from 0.001% to 0.01% uranium, depending on the grade of ore and the extraction process. More importantly, mill tailings contain the totality of the decay products of ^{234}U that were present in the ore extracted from the mine. Because the two precursors of ^{222}Rn are present in the mill tailings, namely ^{226}Ra, with a half-life of 1,600 years, and ^{230}Th, with a half-life of 80,000 years, mill tailings constitute a long-term source of atmospheric ^{222}Rn. Tailings are discharged from mills into open, uncontained piles or behind engineered dams or dikes with solid or water cover. All tailings piles act as sources of airborne releases of ^{222}Rn, although the release rates can be low if the tailings are covered with water.

86. Measurements over bare tailings piles [A8, B8, C8, S8] show that the exhalation rate of ^{222}Rn is about 1 Bq m^{-2} s^{-1} per Bq g^{-1} of ^{226}Ra. Since the concentration of ^{226}Ra in uranium ore with 1% U_3O_8 is approximately equal to 100 Bq g^{-1}, the release rates of ^{222}Rn over bare tailings resulting from the treatment of uranium ore with 0.1%-3% U_3O_8 are expected to range between 10 and 300 Bq m^{-2} s^{-1}; taking the current average ore grade to be 0.2% U_3O_8, the average exhalation rate of ^{222}Rn is expected to be 20 Bq m^{-2} s^{-1}. Reported emission rates of ^{222}Rn for 1985-1989 from mill tailings in Argentina, Australia, Canada and the German Democratic Republic are presented in Table 21. The emission rates per unit area range from 0.1 to 43 Bq m^{-2} s^{-1}, with most of the values centred on 10 Bq m^{-2} s^{-1}, which is an improvement over the emission rates expected from bare tailings. Assuming, as in the UNSCEAR 1988 Report, that the production of a uranium mine generates tailings of about 1 ha $(GW\ a)^{-1}$ and that the release rates of ^{222}Rn remain unchanged during five years, a typical emission rate per unit area of 10 Bq m^{-2} s^{-1} corresponds to a normalized release of ^{222}Rn of about 20 TBq $(GW\ a)^{-1}$. This applies to mill tailings of an operating mill.

87. It is likely that further treatment will be carried out to minimize the releases of ^{222}Rn from abandoned tailings piles. As reported in the UNSCEAR 1988 Report, several techniques were analysed in a study by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD) [O1] for a number of sites. The radon exhalation rate varied by factors of more than 10^6, according to the treatment assumed, showing that this is clearly a crucial parameter in the assessment of the impact of tailings piles. In the UNSCEAR 1988 Report, it was assumed that some reasonably impermeable cover would be used and that the radon exhalation rate from abandoned tailings piles would be 3 Bq m^{-2} s^{-1}. Because of the assumed protection against erosion and of the long radioactive half-life of ^{230}Th, the radon exhalation rate would remain essentially unchanged over at least 10,000 years and would only decrease by a factor of 2 over the next 80,000 years. Further treatment of the abandoned tailings piles by future generations in the next millennium would probably cause a variation in the exhalation rate, which could be either a decrease or an increase. Two extreme options can be envisaged:

(a) to uncover the tailings piles so that the radon exhalation rate would be increased to its initial value of about 20 Bq m^{-2} s^{-1};

(b) to treat the tailings in such a way that the resulting exhalation rate is decreased to 0.02 Bq m^{-2} s^{-1}, which is the average value corresponding to soils in normal background areas.

88. In this Annex, it is assumed that the average ^{222}Rn exhalation rate from abandoned tailings piles is 3 Bq m^{-2} s^{-1} [corresponding to a normalized emission rate of 1 TBq a^{-1} $(GW\ a)^{-1}$] and that this value will remain unchanged over the next 10,000 years. These assumptions of the long-term release of radon are the same as in the UNSCEAR 1988 Report [U1]. It is, however, recognized that the ^{222}Rn exhalation rate could range between 0.02 and 20 Bq m^{-2} s^{-1} any time in the next 10,000 years and beyond. Normalized releases of radionuclides assumed for the mining and milling operations are summarized in Table 22.

2. Dose estimates

89. In the dose estimation procedure used in the UNSCEAR 1988 Report, a reference mine and mill site was considered with population densities of 3 km^{-2} at 0-100 km and 25 km^{-2} at 100-2,000 km. The collective doses resulting from airborne discharges were then calculated using an atmospheric dispersion model with the characteristics of a semi-arid area and an effective release height of 10 m. The resultant collective effective doses per unit release are shown in Table 22, along with the collective effective doses per unit electrical energy generated for the radionuclides released during the operation of the model mine and mill and from the abandoned tailings piles. The total collective effective dose per unit electrical energy generated is estimated to be 1.5 man Sv $(GW\ a)^{-1}$ during the operation of the mine and mill and to be essentially due to the radon releases. This is greater by a factor of 3 than the estimate given in the UNSCEAR 1988 Report, since additional data have indicated higher average normalized releases. The uncertainties exist not only from normalized releases but also from conditions of the model site and the population

distributions. There may be wide deviations from the above assumptions for actual sites. The doses from liquid effluents are negligible in comparison to the doses from airborne effluents.

90. The collective effective dose per unit electrical energy generated that is due to the releases of radon from abandoned tailings piles is estimated to be delivered at a rate of 0.015 man Sv $(GW\ a)^{-1}$ per year of release. The rate of release as a function of time is assumed to be constant, and given the very long radioactive half-lives of the radon precursors, the normalized collective effective dose committed is proportional to the assumed duration of the release. Taking this period to be 10,000 years for the sake of illustration, the result is an estimated 150 man Sv $(GW\ a)^{-1}$. This figure is highly dependent on future management practices; its estimated range is from 1 to 1,000 man Sv $(GW\ a)^{-1}$.

B. URANIUM FUEL FABRICATION

91. The uranium ore concentrate produced at the mills is further processed and purified and converted to uranium tetrafluoride (UF_4), and then to uranium hexafluoride (UF_6) if it is to be enriched in the isotope ^{235}U, before being converted into uranium oxide or metal and fabricated into fuel elements. Uranium enrichment is not needed for gas-cooled, graphite-moderated reactors (GCRs) or heavy-water-cooled, heavy-water-moderated reactors (HWRs). Enrichments of 2%-5% are required for light-water-moderated and cooled reactors (PWRs and BWRs) and for advanced gas-cooled, graphite-moderated reactors (AGRs).

1. Effluents

92. Available data on airborne and liquid discharges from installations of this stage of the fuel cycle are given in Table 23. Emissions of radionuclides from the conversion, enrichment, and fuel fabrication processes are generally small and consist essentially of the long-lived uranium isotopes, ^{234}U, ^{235}U, and ^{238}U, along with ^{234}Th and ^{234m}Pa, which are the short-lived decay products of ^{238}U. The long half-life of ^{230}Th prevents the activity build-up of any other radionuclide of the ^{238}U series. The solid wastes arising during uranium fuel fabrication are trivial in quantity by comparison with those from the uranium mines and mills.

93. The normalized effluent discharges from model fuel conversion, enrichment and fabrication facilities, which are taken to be the same as in the 1988 UNSCEAR Report, are presented in Table 24.

2. Dose estimates

94. Collective doses resulting from the airborne releases were estimated for the model facility specified in the UNSCEAR 1988 Report, with a constant population density of 25 km^{-2} out to 2,000 km. The normalized collective effective dose is estimated to be 2.8 10^{-3} man Sv $(GW\ a)^{-1}$, with inhalation the most important pathway of exposure. The collective doses due to liquid discharges are much less than those from airborne discharges, as was assessed in the UNSCEAR 1982 Report for the same relative releases.

C. REACTOR OPERATION

95. Nearly all the electrical energy generated by nuclear means is produced in thermal reactors. The fast neutrons produced by the fission process are slowed down to thermal energies by use of a moderator. The most common materials used as moderators are light water (in PWRs and in BWRs), heavy water (in HWRs) and graphite (in GCRs and light-water-cooled, graphite-moderated reactors [LWGRs]). The electrical energy generated by these various types of reactors from 1970 to the end of 1989 is illustrated in Figure VII. During this period the number of nuclear reactors increased from 77 to 426; the installed capacity, from 20 to 318 GW; and the energy generated, from 9 to 212 GW a [110]. Basic data on nuclear reactors in operation in 1985-1989 are presented in Table 25.

96. The uranium fuel for the nuclear reactors is contained in discrete pins, which prevent leakage of the radioactive fission products into the coolant circuit. The heat generated in the fuel pins by the slowing down of the fission fragments is removed by forced convection, the most usual coolants being light water (in PWRs, BWRs and LWGRs), heavy water (in HWRs), and carbon dioxide (in GCRs). The thermal energy carried by the coolant is then transformed into electrical energy by means of turbine generators.

97. In addition to the reactor types mentioned above, there are five fast breeder reactors (FBRs) in operation in the world. In that type of reactor, fission is induced by fast neutrons, there is no moderator and the coolant is a liquid metal. The main advantage of the FBR lies in its ability to produce more nuclear fuel than it consumes.

1. Effluents

98. During the production of power by a nuclear reactor, radioactive fission products are formed within the fuel and neutron activation products in structural

and cladding materials. Radioactive contamination of the coolant occurs because fission products diffuse into the coolant from the small fraction of fuel with defective cladding, and particles arising from the corrosion of structural and cladding materials are activated as they are carried through the core. All reactors have treatment systems for the removal of radionuclides from gaseous and liquid wastes.

99. The amounts of different radioactive materials released from the reactors depend on the reactor type, its design and the specific waste treatment plant installed. As in the previous UNSCEAR Reports, annual release data have been compiled for each type of reactor. Annual releases are reported in this Annex for the period 1985-1989. These include:

(a) noble gases (argon, krypton and xenon) released to atmosphere (Table 26); the radionuclide compositions of the noble gases discharged from PWRs and BWRs in the United States in 1988 are given in Tables 27 and 28, respectively;
(b) tritium in airborne effluents (Table 29);
(c) carbon-14 released to the atmosphere, available for a few reactors (Table 30);
(d) iodine-131 in airborne effluents (Table 31); releases of other radioactive isotopes of iodine from PWRs and BWRs in the United States in 1988 are presented in Table 32;
(e) particulates in airborne effluents (Table 33);
(f) tritium in liquid effluents (Table 34);
(g) radionuclides other than tritium in liquid effluents (Table 35); the radionuclide compositions of the activities released in liquid effluents from PWRs and BWRs in the United States in 1988 are given in Tables 36 and 37, respectively.

100. For each effluent category, the reported discharges from individual reactors in a given year vary over several orders of magnitude according to design, type of waste treatment, and level of irregular operations and maintenance. Even for reactors of the same type, the variations are enormous. As an example, the statistical distribution of the ^{131}I released from PWRs in the United States during 1988 is illustrated in Figure VIII. For the distribution assumed to be lognormal, a very large geometric standard deviation of 13 is obtained. Neither the amount of electrical energy generated nor the age of the reactor appears to have a clear effect on the quantities of radioactive materials released in a given year. The normalized releases of radionuclides in airborne effluents from PWRs in the United States in 1988 are illustrated in Figure IX. Both the total and normalized releases seem to be independent of the amount of electrical energy generated in that year or of the age of the reactor. This may indicate that effluent treatments in all reactors are maintained to current standards.

101. The trends in normalized releases from all reactors worldwide of the major components of radionuclides in airborne and liquid effluents are illustrated in Figures X to XVI. Deviations from the general patterns may reflect abnormal operation, special maintenance or the like in specific reactors. Some variability may also reflect data that are too incomplete to provide representative averages. The data become increasingly incomplete for years before 1985. For the period 1985-1989, although some components of discharges are not measured, the reporting of available data is nearly complete for all reactors in operation in the world.

102. Because of the variability in annual releases, normalized releases have been averaged over five-year periods in order to assess the collective doses. The normalized releases for the data available since 1970 are presented in Table 38. Data are available for all types of reactors and effluent categories for 1985 1989, except ^{131}I discharged from FBRs. A release equal to that from PWRs is assumed. Estimated values only are available for ^{3}H releases from LWGRs [I14]. For some earlier periods the data are less complete for some reactor types. In order to include estimates for those periods as well, the more recent data or the data for PWRs are used.

103. The trends in the principal components of releases from reactors, averaged over all reactor types and over five-year time periods from 1970 to 1989, are shown in Figure XVII. Atmospheric discharges of noble gases and iodines, as well as liquid discharges of radionuclides other than tritium, have been decreasing, and there have been less obvious changes for the other components. The downward trends no doubt reflect improvements in the quality of nuclear fuel as well as in the performance and standards of reactors in operation.

104. The estimates of normalized release of radionuclides from reactors may be combined with the electrical energy generated to obtain estimates of the total releases from all reactor operations in the world. A record of energy generation by reactors worldwide is compiled by the International Atomic Energy Agency (IAEA) [I10]. Since this record is not complete, especially for earlier years of operating experience in some countries, data provided separately to the Committee and a few estimated values have been added to provide the summary listing given in Table 39. The average normalized release values in Table 38 are assumed to be the most representative and are applied throughout each five-year period. The total releases from all reactors for the entire period of their usage, during which time 1,844 GW a of electrical energy was generated, and the average normalized releases are given in Table 40.

2. Local and regional dose estimates

105. National authorities usually require that environmental monitoring programmes be carried out in the vicinity of a nuclear reactor. In general, the activity concentrations of radionuclides in effluent discharges are too low to be measurable except close to the point of discharge. Dose estimates for the population therefore rely on modelling the environmental transfer and transport of radioactive materials.

106. In the UNSCEAR 1982 Report and the UNSCEAR 1988 Report, the Committee used a model site that is most representative of northern Europe and the north-eastern United States, since those areas contain a large proportion of all power-producing reactors. The cumulative population within 2,000 km of the model site is about 250 million, giving an average population density of 20 km^{-2}. Within 50 km of the site, the population density is taken to be 400 km^{-2} in order to reflect siting practices. This model site has also been used in this Annex, along with the environmental and dosimetric models of the UNSCEAR 1988 Report. With the exception of ^{3}H and ^{14}C, most of the collective doses are delivered to populations in local and regional areas surrounding the model site. The collective effective dose per unit release for the radionuclides or for the radionuclide compositions representative for each reactor type are presented in Table 41.

107. Estimates of collective effective dose per unit electrical energy generated resulting from effluent discharges from reactors in 1985-1989 are given in Table 42. These are obtained by multiplying the normalized releases (Table 38) by the collective effective dose per unit release (Table 41). The total for all reactor operation is 1.4 man Sv $(GW\ a)^{-1}$.

108. A similar procedure may be used to evaluate the collective dose from the entire period of reactor operation. The average normalized releases in five-year periods (Table 38) are multiplied by the annual energy generation of the different reactor types (Table 39) and by the factors of collective dose per unit release (Table 41). The results for each reactor type are combined in Table 43. The total collective effective dose from all reactor operations through 1989 is estimated to have been 3,700 man Sv. The contributions by each reactor type (not indicated, but determined from the calculation) are 45% from HWRs, 29% from BWRs, 14% from PWRs, 9% from LWGRs, 4% from GCRs and 0.3% from FBRs.

109. The estimated collective effective doses from effluent discharges from reactors have changed over the course of time, as the amounts of electrical energy generated and the released amounts per unit energy generated have changed. Figure XVIII shows the trends for the various effluent categories. The collective doses from atmospheric discharges of noble gases and of iodine and from liquid discharges of radionuclides other than tritium decreased or remained stable from before 1970 through 1985-1989. The other components of the local and regional collective dose increased with time as the quantity of electrical energy generated increased, also shown in Figure XVIII.

110. Individual doses resulting from routine releases of radioactive effluents from reactors are usually low. For the model site, the annual effective doses to most exposed individuals are estimated to be 1 μSv for PWRs, 7 μSv for BWRs, 10 μSv for HWRs, 10 μSv for GCRs, 20 μSv for LWGRs and 0.1 μSv for FBRs.

D. FUEL REPROCESSING

111. At the fuel reprocessing stage of the nuclear fuel cycle, the elements uranium and plutonium in the irradiated nuclear fuel are recovered to be used again in fission reactors. Spent fuel elements are preferably stored under water for a minimum of four to five months, in order to ensure that the short-lived ^{131}I decays to a very low level. Since one reprocessing plant can serve a large number of nuclear reactors, the quantities of radionuclides passing through the plant are high in absolute terms.

112. Reprocessing is, at present, carried out in only a few countries and is limited to a small portion of the irradiated fuel. Known reprocessing capacities, as summarized in Table 44, amount to about 3,300 t of uranium per annum. The annual throughputs of irradiated fuel from civilian power programmes to fuel reprocessing plants in France, Japan and the United Kingdom are illustrated in Figure XIX. In the 1980s the total throughput at these plants ranged from an equivalent of 5 to 8.5 GW a of electrical energy, representing 5% of the annual worldwide nuclear electrical energy production in that period. The fraction of irradiated fuel that is reprocessed has been decreasing slightly with time, as energy production has expanded somewhat more than the throughput of fuel at the reprocessing plants. The fractional amounts reprocessed in terms of energy production equivalent were 0.078, 0.066 and 0.04 during 1975-1979, 1980-1984 and 1985-1989, respectively. The data for years before 1975 are incomplete.

113. Several countries have taken decisions not to reprocess fuel. In these countries, the fuel will either be disposed of or stored retrievably; in the latter case the possibility of reprocessing at some later date

would not be precluded. The current strategy for the management of spent fuel in different countries is summarized in Table 45; in each case the amount of irradiated fuel produced in 1990 is indicated, based on the amount of nuclear energy generated in that year. For the countries included in Table 45, the generation of spent oxide fuel in 1990 was about 11,000 t of uranium.

1. Effluents

114. The radionuclides of principal concern in effluents from reprocessing plants are the long-lived nuclides: ^{3}H, ^{14}C, ^{85}Kr, ^{129}I, ^{134}Cs, ^{137}Cs and isotopes of transuranium elements. The reported releases of radionuclides to the atmosphere and to the sea from the Sellafield, Cap de La Hague and Tokai-Mura reprocessing plants for 1985-1989 are listed in Table 46. In this Table, the values for the electrical energy generated that correspond to the annual throughput of fuel were estimated from the ^{85}Kr discharges, using production rates of 14 PBq $(GW\ a)^{-1}$ for GCRs and 11.5 PBq $(GW\ a)^{-1}$ for PWRs. The variations with time of the normalized releases of ^{3}H and ^{137}Cs in liquid effluents from the Cap de La Hague and Sellafield reprocessing plants are illustrated in Figure XX. The annual total releases follow a similar pattern. Discharges of tritium have been increasing slightly, but ^{137}Cs releases have been decreasing. Stricter controls on releases from the Sellafield plant have, since the early 1980s, reduced the ^{137}Cs releases to levels comparable to those from the Cap de La Hague plant. The normalized releases from the Tokai-Mura plant have been comparable to those from the European plants for ^{3}H but several orders of magnitude less for ^{137}Cs.

115. The data in Table 46, along with those quoted in previous UNSCEAR Reports [U1, U3, U4] and additional data from Japan [N13], have been used to determine the average normalized releases of radionuclides during the five-year periods. The limited data prior to 1975 have been combined with later data to provide estimates for 1970-1979. The values are given in Table 47. The normalization is relevant to the equivalent energy production of the fuel reprocessed. Tritium releases in liquid effluents increased in the most recent five-year period, but there have been decreases for most other radionuclides, particularly for ^{137}Cs (by a factor of 80), for ^{90}Sr (by a factor of 13) and for ^{106}Ru (by a factor of 9).

116. The total amounts of radionuclides released from fuel reprocessing can be estimated by completing the record of amounts of fuel reprocessed prior to 1975. For this purpose the ratio of 0.078 times the annual electrical energy generated by reactors has been used. The energy generated by reactors was given in Table 39. The fuel reprocessed (energy equivalent) times the average normalized releases of Table 47 give estimates of the total annual releases, which are shown in Table 48. Whenever the measured results from all three reprocessing plants in France, Japan and the United Kingdom were available, those results, instead of estimated values, were used in Table 48. Measured results were available for ^{3}H and ^{85}Kr in airborne effluents and ^{3}H, ^{90}Sr, ^{106}Ru, ^{137}Cs in liquid effluents since 1975, for ^{129}I in airborne effluents in 1980-1984 and in liquid effluents in 1983-1986. The average normalized releases for the entire period of fuel reprocessing operations given in Table 48 correspond to 1,844 GW a of electrical energy generated and an amount of fuel reprocessed equivalent to 101 GW a.

2. Local and regional dose estimates

117. The collective doses from the reprocessing of nuclear fuel arise from local and regional exposures and from exposures to the globally dispersed radionuclides. Estimates of the local and regional dose commitments are given in this Section and the global contribution in Section E. The local and regional collective doses per unit release of radionuclides were evaluated in the UNSCEAR 1988 Report [U1]. These values are included in Table 49 along with the normalized release amounts derived in Table 46. The product of these two quantities gives the collective effective dose per unit energy equivalent of fuel reprocessed. Since the total fuel reprocessed in 1985-1990 was 4% of the total, the collective dose normalized to the total energy generated in the period is less by the factor 0.04. The total normalized collective effective dose (relative to total energy generated) is 0.05 man Sv $(GW\ a)^{-1}$ from airborne effluents and 0.2 man Sv $(GW\ a)^{-1}$ from liquid effluents.

118. The evaluation of the collective dose for the entire period of fuel reprocessing is straightforward from the estimates of annual releases of radionuclides presented in Table 48. The quantities in this table are multiplied by the factors of collective dose per unit release in Table 49. The results are presented in Table 50. The collective dose from the start of the reprocessing practice is estimated to be 4,600 man Sv. The main components (over 90%) of the dose are ^{137}Cs and ^{106}Ru in liquid effluents.

119. Annual individual doses to critical groups have been evaluated for the three reprocessing plants for which release data are available. Individual doses for Sellafield have been derived from environmental monitoring data, combined with information on the habits of local critical groups [C4]. The main path-

ways considered are the consumption of locally caught fish and shellfish, whole body external irradiation from intertidal areas and external irradiation of the skin of fishermen while handling nets and pots. Annual individual doses to critical groups by the ingestion pathway peaked at about 3.5 mSv in the early 1980s and later declined, to about 0.2 mSv in 1986. The estimated annual individual doses to the critical group for whole body exposure to external irradiation also peaked in the early 1980s at about 1 mSv and decreased to about 0.3 mSv in 1986. Finally, the measured beta dose rates from nets and pots have suggested that skin exposure to fishermen would be no more than 0.1 mSv a^{-1} [C4]. The exposure pathways for critical groups are similar for the fuel reprocessing plant at Cap de La Hague. The estimated annual individual doses for 1986 are 0.2 mSv for the consumption of fish and shellfish and 0.05 mSv for whole body external irradiation. The annual doses to critical groups near the Tokai-Mura reprocessing plant are of the order of 1 μSv [S3].

E. GLOBALLY DISPERSED RADIONUCLIDES

120. The radionuclides giving rise to global collective doses are those that are sufficiently long-lived and that migrate readily through the environment, achieving widespread distribution. The radionuclides of interest are ^{3}H, ^{14}C, ^{85}Kr and ^{129}I. The very long-lived ^{129}I poses a special problem because of the uncertainties involved in the prediction of population size, dietary habits and environmental pathways over periods of tens of millions of years. In this Annex, the global dose commitments are truncated at 10,000 years. By that time, ^{3}H and ^{85}Kr have decayed to insignificant levels and ^{14}C has decayed to about 30% of its initial value. Results for alternative integration periods were presented in the UNSCEAR 1988 Report [U1]. The limit of 10,000 years was chosen to correspond to the maximum period of integrity of tailings piles from which ^{230}Th continues to support ^{222}Rn emanation. Beyond 10,000 years either complete erosion or massive covering of the tailings would occur due to the expected intervention of an ice age. The uncertainties of dose calculations become exceedingly great as integration periods are extended over thousands of years.

121. The collective effective dose per unit electrical energy generated is evaluated in Table 51. The normalized release from reactors and reprocessing plants, the latter less by a factor of 0.04 when normalized for the total energy generated, representing the fraction of fuel reprocessed, is multiplied by the factors of collective dose per unit release. For tritium, the collective dose per unit release to air is taken to correspond to the quotient of the annual dose rate to the hemispheric production rate of natural tritium (10 nSv a^{-1} ÷ 37 PBq) times the world population of the northern hemisphere (5 10^{9} × 0.89). The result is 0.0012 man Sv TBq^{-1}. For release to sea, calculations with a global circulation model have shown that the normalized collective dose is a factor of 10 less [N8]. For ^{14}C, the collective dose per unit release is taken to be 85 man Sv TBq^{-1}, which over the 10,000-year period is 71% of the normalized collective dose committed for all time (see paragraph 44). For ^{85}Kr and ^{129}I, the collective dose factors are taken to be as evaluated in the UNSCEAR 1988 Report [U1]. The normalized collective dose, truncated at 10,000 years, from globally dispersed radionuclides is 53 man Sv $(GW\ a)^{-1}$ and is due almost entirely to ^{14}C.

122. The total collective effective dose from globally dispersed radionuclides for the entire period of nuclear power production can be evaluated by multiplying the total release of these radionuclides by the collective dose per unit release. The results of this calculation are given in Table 52. The total is 123,000 man Sv, over 99% of which is due to ^{14}C.

F. SOLID WASTE DISPOSAL AND TRANSPORT

123. The solid wastes that arise from reactor operations as well as from the handling, processing and disposal of spent fuel are generally characterized as low-level wastes, intermediate-level wastes, and high-level wastes. Low-level wastes and intermediate-level wastes are generally disposed of by shallow burial. Burial facilities range from simple trenches or pits containing untreated wastes and capped with soil (typically used for low-level wastes) to concrete structures containing conditioned wastes and capped with soil (typically used for intermediate-level wastes). Some low-level wastes were disposed of at sea at more than 50 sites from 1946 to 1982 [I11]. Various solutions are envisaged for the disposal of high-level wastes, but none have yet been implemented. Decommissioned reactors will become part of solid waste management programmes in the future. Several reactors have been shut down, but none have yet been dismantled or transformed into a waste disposal site as yet.

124. Doses from solid waste disposal are usually assumed to result from the migration of radionuclides through the burial site into groundwater. The normalized collective effective dose attributable to wastes from reactor operation is almost entirely due to ^{14}C and roughly amounts to 0.5 man Sv $(GW\ a)^{-1}$; the corresponding value for wastes from the handling and processing of spent fuel is 0.05 man Sv $(GW\ a)^{-1}$.

These estimates are highly uncertain as they depend critically on the assumptions used for the containment of the solid wastes and for the site characteristics.

125. Materials of various types are transported between the installations involved in the nuclear fuel cycle. Members of the public in the vicinity of the trucks, boats or trains carrying the radioactive materials are exposed to small doses of external irradiation. On the basis of fragmentary data, the normalized collective effective dose was estimated to be 0.1 man Sv $(GW\ a)^{-1}$ in the UNSCEAR 1988 Report. The same value is used in this Annex.

G. SUMMARY OF DOSE ESTIMATES

126. A summary of the main contributions to the total collective effective dose, normalized per unit electrical energy generated, is shown in Table 53. The local and regional normalized collective effective doses, which are effectively received within one or two years of discharge, amount to 3 man Sv $(GW\ a)^{-1}$ and are principally due to routine atmospheric releases during reactor and mining operations. Even though the contributions from the various components of the nuclear fuel cycle are different from those reported in the UNSCEAR 1988 Report, the total remains the same, as the decreases in the dose estimates from reactor operation and fuel reprocessing have been compensated by increases in the dose estimates from mining and milling. Globally dispersed radionuclides in effluents from the nuclear fuel cycle and long-term releases from solid waste disposal result in small exposures to members of the public over a very long time (10,000 years or more). The normalized collective effective dose received within 10,000 years amounts to about 200 man Sv $(GW\ a)^{-1}$ and is mainly due to the release of radon from mill tailings and to the release of ^{14}C from fuel reprocessing plants and from reactors.

127. The assessment of the local and regional collective dose for the entire period of nuclear power production has been determined for reactor operation, 3,700 man Sv (Table 43), and for fuel reprocessing, 4,600 man Sv (Table 50). It can be assumed that the normalized collective effective dose from mining and milling, given as 1.5 man Sv $(GW\ a)^{-1}$ in Table 53, is also representative of earlier periods. The total collective dose from this portion of the fuel cycle is thus 1.5 man Sv $(GW\ a)^{-1} \times 1{,}844$ GW a = 2,700 man Sv. The total for the entire fuel cycle is 2,700 + 3,700 + 4,600 = 11,300 man Sv. The average normalized collective dose for the entire period of the practice is estimated to be 11,000 man Sv ÷ 1,844 GW a = 6 man Sv $(GW\ a)^{-1}$. This long-term average is higher than the value for present practice owing to the declining releases from reactors and fuel reprocessing operations.

128. The estimation of collective effective doses from globally dispersed radionuclides and from long-term releases from solid waste disposal is rather speculative, as it depends heavily on future waste management practices and on the evolution of the world's population over the next 10,000 years. Multiplying the figure of 200 man Sv $(GW\ a)^{-1}$ obtained in this Annex as well as in the UNSCEAR 1988 Report by 1,844 GW a yields a collective effective dose from these sources of about 400,000 man Sv. About 25% of the total is due to ^{14}C released from reactors and reprocessing plants (Table 52) and the remainder to radon released from mill tailings.

V. RADIOISOTOPE PRODUCTION AND USE

129. Radionuclides are used for a variety of purposes in industry, medicine and research [16], and both the number of uses and the quantities used have been continually increasing. For example, in Japan, the number of establishments using radionuclides and/or radiation generators has grown over the years, from about 100 in 1960 to about 5,000 in 1990 [J2]. Exposures of the public may result from activities associated with the production, use and waste disposal of the radioactive materials. The doses from the use of radioisotopes in consumer products were considered in the UNSCEAR 1982 Report [U3]. The doses evaluated in this Chapter are those resulting from releases to the environment, which may occur during production, use or disposal. Radionuclides produced for sealed sources are not considered, since they are not normally released. Radiopharmaceuticals, ^{14}C and ^{3}H are usually eventually released, and with some approximation the total production can give an estimate of the total release.

A. PRODUCTION AMOUNTS AND RELEASES

130. The amounts of radioisotopes produced for commercial or medical purposes are not well documented. Likewise, the releases during production

or use are not widely reported. The evaluation of doses must therefore remain rather approximate, with only preliminary, very uncertain results having been used. Statistics on radioisotope production and use are available only for Japan [J2]. Table 54 gives the annual uses of radioisotopes in 1989 in hospitals, schools, research institutions and industries. From the population of Japan (118.9 million) the usage per 10^6 population may be determined: for example, 5.2, 6.1, 14 and 34 GBq per 10^6 population for ^{14}C, ^{125}I, ^{3}H and ^{131}I, respectively.

131. The production of compounds labelled with ^{14}C has been estimated for the United States in 1978 to be about 7 TBq [N9], corresponding to 30 GBq per 10^6 population. This is six times the normalized usage in Japan. The production amount of ^{14}C in the United Kingdom is not available, but the reported releases in airborne and liquid effluents from the commercial production plant were reported to be 3.2 TBq in 1987 [H6]. This corresponds to 55 GBq per 10^6 population. The net production must be substantially greater. It is, however, supporting users in many other countries as well as in the United Kingdom. By assuming that 10% of the ^{14}C is lost at production and normalizing to the population of Europe (roughly 10 times that of the United Kingdom), the estimate of normalized production becomes 50 GBq per 10^6 population.

132. To obtain approximate figures of production, usage and ultimate release amounts, the ^{14}C estimate of the United States is assumed and applied at the rates of 100% to the population of developed countries ($1.2\ 10^9$ population) and 10% to the population of developing countries ($3.7\ 10^9$ population). The annual production and release of radioisotopes relative to ^{14}C are determined from the values given in Table 54 for Japan. Thus, for example, the production of ^{3}H and ^{131}I is three and six times greater, respectively, than the production of ^{14}C.

133. The annual global production and ultimate release of these radionuclides may be estimated to be 30 GBq per 10^6 population (^{14}C) times an equivalent world population of $1.6\ 10^9$ persons times the relative production fractions. The results for several radionuclides are given in Table 55. Other radionuclides not included in this Table, especially those in solid form, are unlikely to be released or widely dispersed from the end-uses.

134. Additional data on the production and release of radioisotopes are available for ^{131}I administered to patients in medical facilities. The total amount of ^{131}I produced for medical purposes in Sweden during 1986 was 0.9 TBq [N15]. Radioactive discharges of ^{131}I from hospitals in Australia in 1988-1989 have been reported as 2.9 TBq [A9]. These amounts, corresponding to 110 and 190 GBq per 10^6 population, give some corroboration to the value used in Table 55 (200 GBq per 10^6 population). About two thirds of orally administered ^{131}I is excreted via the urine of treated patients in the first day [E2]; however, only very low concentrations of ^{131}I have been measured in surface waters in Germany [A7] and in the sewage systems of cities in Sweden [E2] and in the United States [S5]. Waste treatment systems in hospitals with hold-up tanks may reduce the amounts of ^{131}I discharged in liquid effluents to $5\ 10^{-4}$ of amounts administered to patients [J3].

B. DOSE ESTIMATES

135. Since the environmental levels of radioisotopes used for medical, educational or industrial purposes are in general undetectable, only approximate, calculated estimates can be made of the collective doses. The results are given in Table 55. The estimates assume no partial retention of the radionuclides in end-products and no hold-up prior to wide dispersion and the exposure of local, regional or global populations. This could result in overestimated doses, significantly so for radioiodines that have short half-lives. The dose coefficients listed in Table 55 are those derived and used for radionuclides produced and released in nuclear power production. Tritium and the noble gases are assumed to be released to the atmosphere, ^{14}C to be released in both airborne and liquid effluents and ^{131}I and ^{125}I to be released to rivers. There could be occasional release of iodine in airborne effluents, for example from incineration of waste materials. This would be easily detected, but since it is so seldom reported, it can be assumed that this is not an important source of release. The dose coefficient for ^{125}I is based on age-weighted dose-per-unit-intake values [N1] and the ^{125}I half-life of 13 hours, with other model parameters the same as for ^{131}I.

136. The total local and regional collective effective dose from releases of radioisotopes used in one year in medical and industrial applications is of the order of 100 man Sv. If it can be assumed that the practice of these radioisotope uses has been building up over the past 40 years, the collective dose committed from all past releases would be 20 times the present annual value, or 2,000 man Sv in total. The global component of the collective effective dose, arising almost entirely from ^{14}C, is 4,000 man Sv from one year of radioisotope usage and 80,000 man Sv committed from the entire practice to date. The contribution of this source to man-made exposures in general is thus relatively unimportant on an annual basis. The doses from ^{14}C are at low dose rate but extend over a long period of time.

VI. ACCIDENTS

137. A number of accidents have occurred at both civilian and military nuclear installations and in the transport of nuclear materials. In some cases, there was substantial contamination of the environment. These accidents are discussed in this Chapter, and the magnitude of population doses incurred are estimated.

A. CIVILIAN NUCLEAR REACTORS

138. The two principal accidents involving installations of the civilian nuclear fuel cycle took place at the Three Mile Island reactor in the United States in March 1979 and at Chernobyl in the USSR in April 1986.

1. Three Mile Island

139. The accident at Three Mile Island has been the subject of many reports, particularly from the United States Nuclear Regulatory Commission and the President's Commission [K3]. The cause of the accident was the failure to close a pressure relief valve, which led to severe damage of uncooled fuel. The accident released large amounts of radioactive materials from failed fuel to the containment, but the environmental releases were relatively small (about 370 PBq of noble gases, mainly ^{133}Xe, and 550 GBq of ^{131}I into the atmosphere).

140. Individual doses averaged 15 μSv within 80 km of the plant, and the maximum effected dose that any member of the public could have received is estimated to have been 850 μSv from external gamma irradiation [K3]. The collective effective dose due to the release has been estimated to be 20 man Sv within 80 km of the plant [K3]. The contribution to the effective dose commitment due to ^{133}Xe dispersion beyond 80 km may have been equal to that within 80 km [U3], which gives a total of 40 man Sv.

2. Chernobyl

141. The worldwide exposures from the Chernobyl accident were evaluated in detail in the UNSCEAR 1988 Report [U1]. In the course of a low-power engineering test, uncontrollable instabilities developed and caused explosions and fire, which damaged the reactor and allowed radioactive gases and particles to be released into the environment. The fire was extinguished and the releases stopped by the tenth day after the accident. The death toll within three months of the accident was 30, all of them members of the operating staff of the reactor or of the fire-fighting crew.

142. The total release of radioactive materials is estimated to have been 1-2 EBq [I3], the principal radionuclides being ^{131}I (630 PBq), ^{134}Cs (35 PBq) and ^{137}Cs (70 PBq) [I15]. The proportional amounts dispersed beyond the USSR were determined to be 34% for ^{131}I and 56% for ^{137}Cs [I15].

143. About 115,000 residents were relocated from a 30 km exclusion zone surrounding the reactor. The external radiation doses to most of those evacuated was less than 0.25 Sv, although a few in the most contaminated areas might have received doses up to 0.3-0.4 Sv. The collective dose from external radiation to the evacuees is estimated to have been 16,000 man Sv. Individual thyroid doses to children may have been 2.5 Gy and higher in some cases, with an average thyroid dose of 0.3 Gy and a collective thyroid dose of 400,000 man Gy [C10].

144. The radiation situation beyond the 30 km zone surrounding the reactor was determined primarily by the wind directions. When rainfall occurred at the time that the radioactive cloud was passing, the deposition density of ^{137}Cs and other fission radionuclides was enhanced. In the USSR, an area of about 10,000 km^2 was contaminated with ^{137}Cs to levels in excess of 560 kBq m^{-2}, and an area of 21,000 km^2 received upwards of 190 kBq m^{-2} [I15]. A government commission determined that 786 settlements, located in Belarus, the Russian Federation, and Ukraine, with a population of 270,000, were to be considered as "strict control zones". Protective measures preventing the consumption of contaminated foodstuffs were applied in the strict control zones. The average effective dose received by the populations in the strict control zones is estimated to have been 37 mSv in the year following the accident and 23 mSv in 1987-1989 [I15]. An international review project was conducted in 1990 to investigate environmental levels, doses and the health of residents of unevacuated settlements [I1]. The project corroborated results of measurements and dose evaluations. Diet and body measurements showed that agricultural practices and protective measures were effective in limiting exposures. The doses determined by whole body counting were less than expected from calculation by environmental models. Estimation of thyroid doses requires interpretation of early direct measurements and calculation of presumed ^{131}I intakes; these doses are thus subject to considerable uncertainties.

145. Detailed information on environmental contamination levels and radiation doses received by populations in the northern hemisphere was made available to the Committee by many countries, either

directly to the UNSCEAR secretariat or in published reports. This information enabled the Committee, in the UNSCEAR 1988 Report [U1], to calculate first-year radiation doses in the USSR, all other European countries and a few other countries in the northern hemisphere. The projected doses beyond the first year were based on the environmental behaviour of ^{137}Cs determined in many years of measurements following atmospheric nuclear testing.

146. The collective effective dose from the Chernobyl accident was estimated to be approximately 600,000 man Sv [U1]. Of this amount, 40% is expected to be received in the territory of the former USSR, 57% in the rest of Europe and 3% in other countries of the northern hemisphere.

B. MILITARY INSTALLATIONS

147. There have been two accidents at military plants that are known to have caused measurable exposures of the public: an accident at Kyshtym in the southern Ural Mountains of the USSR in September 1957 and the Windscale reactor accident in the United Kingdom in October of the same year.

1. Kyshtym

148. In the early 1950s high-level radioactive wastes from the Chelyabinsk-40 plutonium production centre near Kyshtym were stored in water-cooled tanks encased in concrete. The corrosion and failure of process monitoring equipment led to a breakdown in the cooling system of a 300 m^3 tank, allowing the 70-80 tonnes of waste, stored mainly in the form of nitrate and acetate compounds and containing about 1 EBq of radioactive materials, to heat up. The water in the tank evaporated, and as the sediments dried out, they reached temperatures of 330-350°C. On 29 September 1957 the contents of the tank exploded with a power estimated to have been equivalent to 70-100 tonnes of TNT [R3]. About 90% of the radioactive materials contained in the tank deposited locally, while the remainder (about 100 PBq) was dispersed away from the site of the explosion [A4, B11, B12, N2, N3, R3, T1, T4]. The main contributors to the total activity associated with the radioactive materials released were ^{144}Ce + ^{144}Pr (66%), ^{95}Zr + ^{95}Nb (24.9%), ^{90}Sr + ^{90}Y (5.4%) and ^{106}Ru + ^{106}Rh (3.7%). In addition, ^{137}Cs (0.036%), ^{89}Sr (traces), ^{147}Pm (traces), ^{155}Eu (traces) and $^{239,240}Pu$ (traces) were also released [B11]. With the exception of caesium, the radionuclide composition is similar to that of fission products that had been cooled for about one year. Waste treatment at the reprocessing plant involved concentrating the radionuclides by means of precipitation with sodium hydroxide. Caesium was practically the only element with radionuclides that remained in the solution; it was later concentrated separately [R3].

149. The radioactive cloud reached a height of about 1 km. Wind conditions were relatively stable during the dispersion of the cloud over a relatively flat surface, and there was no precipitation. This resulted in an oblong fallout area, extending to about 300 km from the plant, with a clearly defined axis and monotonic decrease in the deposition density along the axis and perpendicular to it. Virtually all of the deposition occurred within 11 h. The boundaries of the contaminated area were taken to correspond to a ^{90}Sr deposition density of 4 kBq m^{-2}, twice the level of global fallout.

150. Redistribution of the deposited radionuclides occurred to some extent, most noticeably in the first few days after the accident. The main sources of the redistribution were the crowns of trees and the soil surfaces. On the whole, the delineation of the fallout area was practically complete by 1958, when wind migration was redistributing less than 1% of the original fallout. Over the next 30 years, wind transfer did not affect appreciably the distribution of the contamination [T1]. The contaminated area was estimated to comprise between 15,000 and 23,000 km^2, with a population of about 270,000, in the provinces Chelyabinsk, Sverdlovsk and Tyumen [B11, N3]. There were 1,154 people in areas with a ^{90}Sr deposition density greater than 40 MBq m^{-2}, 1,500 in areas with a deposition greater than 4 MBq m^{-2} and 10,000 in areas with a deposition greater than 70 kBq m^{-2} [B11, N3].

151. External irradiation was the main route of exposure during the first few months after the accident; subsequently, the ingestion of ^{90}Sr in foodstuffs became predominant. During the initial period, the dose rate in air was about 1.3 μGy h^{-1} from gamma emitting radionuclides in areas with a ^{90}Sr deposition density of 40 kBq m^{-2}, with maximum values of about 5 mGy h^{-1} near the plant, where the deposition density of ^{90}Sr reached 150 MBq m^{-2} [B11]. Within 10 days of the accident 1,154 persons [B11, B12, N3, R3] were evacuated from the settlements in the most severely affected area, which had a ^{90}Sr deposition density greater than 40 MBq m^{-2}. Subsequently, monitoring of the radioactive contamination levels in foodstuffs and agricultural produce was carried out to assure that an annual ^{90}Sr intake of 50 kBq a^{-1} would not be exceeded. A ban on foods was imposed with concentration limits of ^{90}Sr relative to the mass of calcium in foods of 7.4 Bq g^{-1} initially and 2.4 Bq g^{-1} at a subsequent period. This led to the destruction of more than 10,000 tonnes of agricultural produce in the first two years following the accident and to the

decision to carry out a further systematic evacuation of the population from areas with a ^{90}Sr deposition density greater than 150 kBq m^{-2} [R3]. The resettlement, which began 8 months after the accident, was completed 18 months after the accident. Altogether, 10,730 persons were evacuated [B11]. The collective dose is evaluated in Table 56. The average dose received by the population group evacuated within 10 days of the accident was 170 mSv from external irradiation and 1,500 mSv to the gastro-intestinal tract; the average effective dose was 520 mSv. The collective dose received by the evacuated individuals amounted to about 1,300 man Sv.

152. The doses received by the populations that were not evacuated are also presented in Table 56. About half of the effective dose had been delivered within one year, more than 90% within 10 years and nearly all within 30 years of the accident. The effective dose per unit deposition density was estimated to be 320 μSv per kBq m^{-2} over 30 years, with just over 20% due to external irradiation. The collective effective doses received by the non-evacuated population (about 260,000 persons) have been reported to be 1,100 man Sv [N3] and about 5,000 man Sv [B1]. It is difficult to judge the validity of these figures, as the information on the correspondence of ^{90}Sr deposition densities with populations is very coarse. However, it is indicated that average effective doses received over 30 years are estimated to have been 20 mSv for a group of about 10,000 people living in areas with a ^{90}Sr deposition density between 40 and 70 kBq m^{-2} and 4 mSv for a group of 2,000 people living in areas with a deposition density between 4 and 40 kBq m^{-2} [B11]. On the basis of the relationship between population and the deposition density of ^{90}Sr described above, it can be assumed that the number of people living in areas with deposition densities between 40 and 70 kBq m^{-2} was 10,000 and that the number of people living in areas with deposition densities between 4 and 40 kBq m^{-2} was 250,000, resulting in a collective effective dose over 30 years of 1,200 man Sv.

153. A less serious accident occurred in 1967, as a consequence of the disposal of radioactive wastes containing 4 EBq of ^{90}Sr and ^{137}Cs radioactive wastes in Lake Karachay [A3, N4, T4]. On that occasion, dust from the lake bed or the shore-line, containing about 20 TBq of ^{90}Sr and ^{137}Cs, was dispersed by the wind over an area of 1,800 km^2 and to a distance of up to 75 km. The contaminated territory included portions under the radioactive plume of the 1957 accident. The maximum deposition density of ^{90}Sr was 0.4 MBq m^{-2}, and the $^{137}Cs/^{90}Sr$ activity ratio was 3. Specific information on the doses resulting from that accident is not available; it is expected that they are included in the doses from the much more serious accident that occurred in 1957 at the same site. However, because the $^{137}Cs/^{90}Sr$ activity ratios were very different in the 1957 and 1967 accidents, it would be possible, as evidenced by recent measurements [A3], to separate the contributions from the two accidents by analysing soil samples.

2. Windscale

154. The accident at Windscale in October 1957 began during a routine release of the Wigner energy stored in the graphite of the gas-cooled reactor. Owing to errors in operation, the fuel became overheated and caught fire. The fire lasted for about three days. Major releases of radionuclides occurred mainly in two periods: when the air flow was re-started through the core soon after the accident started, in an attempt to cool it, and when water was pumped into the reactor to extinguish the fire on the second day of the accident [C13]. The release of ^{131}I is estimated to have been 740 TBq, accompanied by 22 TBq of ^{137}Cs, 3 TBq of ^{106}Ru and 1.2 PBq of ^{133}Xe [C10]. In addition to the fission products, other radionuclides were released, the most notable being ^{210}Po, which was being produced by neutron irradiation of bismuth ingots in the core. The release of ^{210}Po amounted to 8.8 TBq [C10, C14]. The Windscale reactor has not been used again since.

155. The contamination of pasture land was widespread, the majority of the released radioactive materials having passed south-south-east of Windscale, in the direction of London, and eventually over Belgium before having turned northwards, to Norway. At the time of accident, the radionuclide identified as being of principal concern was ^{131}I, and the main pathway to man was identified as the ingestion of cow's milk. The prompt imposition of a ban on milk supplies had the effect of reducing ^{131}I intakes via the pasture-cow-milk-pathway [C10]. Extensive environmental measurements were made in the United Kingdom at the time of the accident. Maximum doses to persons close to the site were estimated to have been of the order of 10 mGy to the thyroid of adults and perhaps 100 mGy to the thyroid of children [B2, C9]. Thyroid doses to adults in Leeds and London were estimated from measurements of ^{131}I in the thyroids to have been 1 mGy and 0.4 mGy, respectively [B2], with young children having received doses twice as great.

156. The collective effective dose received in the United Kingdom and in Europe from all radionuclides and pathways was estimated to have been 2,000 man Sv, of which about 900 man Sv was due to inhalation and 800 man Sv was due to the ingestion of milk and other foodstuffs. External irradiation from

ground deposits of radionuclides was estimated to have contributed 300 man Sv. The main contributors to the collective effective dose were ^{131}I (37%) and ^{210}Po (37%), followed by ^{137}Cs (15%) [C10].

C. TRANSPORT OF NUCLEAR WEAPONS

157. Fourteen accidents involving aircraft carrying nuclear weapons or components of nuclear weapons are known to have occurred, the two most publicized being the aircraft crash near Palomares, Spain, in January 1966 and the crash at Thule, Greenland, in January 1968. Appreciable amounts of ^{239}Pu were released locally to the environment. A number of nuclear weapons have also been lost at sea.

158. The accident at Palomares, on the Mediterranean coast, occurred on 17 January 1966, when two United States military planes collided in the process of a mid-air refuelling operation. The parachutes of two of the four thermonuclear weapons carried by one of the planes failed to deploy, resulting in the detonation of their conventional explosives and the release of their fissile material upon hitting the ground. Partial ignition of the fissile material formed a cloud that contaminated 2.26 km^2 of uncultivated farm land and urban land with ^{239}Pu and ^{240}Pu [I16-I20]. The other two bombs were recovered intact, one in a dry river bed near the mouth of the Almanzora River and the other in the sea.

159. Where the deposition density of alpha emitters was greater than 1.2 MBq m^{-2} (an area of 22,000 m^2), the contaminated vegetation and a surface layer of soil, approximately 10 cm deep, were collected, separated and disposed of as radioactive waste. Arable land with levels below 1.2 MBq m^{-2} was irrigated, ploughed to a depth of 30 cm, harrowed and mixed. On rocky hillsides, where ploughing was not possible, soil with a plutonium level greater than 0.12 MBq m^{-2} was removed to some extent with hand tools [I17].

160. Estimates of the doses from inhalation and from ingestion have been derived from measured concentrations of ^{239}Pu and ^{240}Pu in ground-level air, in agricultural foodstuffs and in people. The urine and lungs of Palomares inhabitants have been sampled and measured for plutonium since 1966. Of the 714 people examined up to 1988, only 124 showed concentrations of plutonium in urine greater than the minimum detectable activity. Iranzo et al. [I18] estimated that the 70-year committed effective doses for 55 of these people ranged from 20 to 200 mSv owing to the acute inhalation of radioactive particles at the time of the accident or immediately afterwards. The highest estimated 70-year committed effective dose was 240 mSv to a one-year-old child [I18]. From data in this reference, the collective effective dose due to acute inhalation of radioactive particles immediately after the accident can be estimated to have been about 1 man Sv.

161. The resuspension of soil particles has been monitored since 1966 at four locations [I17]. The average annual concentrations of ^{239}Pu and ^{240}Pu during the period 1966-1980 were 5.5 μBq m^{-3} at the location representative of the urban centre and 52 μBq m^{-3} at the location representative of the most exposed farming area [I17]. The corresponding 50-year effective dose per year of intake by inhalation of radioactive particles resuspended from soil are 4 and 35 μSv per year of intake for people in the urban area and in the most exposed farming area, respectively. Assuming that (a) the total number of persons exposed is 714; (b) 90% of that exposed population resides in the urban area and the remainder in the most exposed farming area; and (c) the amount of ^{239}Pu and ^{240}Pu available for resuspension decreases exponentially with a half-time of 100 years, the collective effective dose due to the resuspension of radioactive particles is roughly estimated to be 1 man Sv.

162. The main crops in the cultivated area of the Palomares region are tomatoes, barley and alfalfa [I20]. From the plutonium concentrations in those products, it can be inferred that resuspension of the plutonium particles in soil plays a more important role than absorption through root uptake in the contamination of agricultural products cultivated in the area [I20]. Iranzo et al. [I20] estimated that the individual committed effective dose due to a yearly consumption of unwashed contaminated tomatoes would be 1.5 μSv and that the collective effective dose from a yearly consumption of tomatoes grown on one hectare of contaminated soils would be 10^{-4} man Sv. Assuming that (a) the cultivated area used for the production of tomatoes is 100 hectares (1 km^2) and (b) the amount of plutonium available for the contamination of agricultural crops decreases exponentially with a half-time of 100 years (reflecting the predominant role of resuspension), the collective effective dose due to the ingestion of tomatoes contaminated as a result of the accident is crudely estimated to be about 1 man Sv. The contamination of barley and alfalfa also results in the contamination of products used for human consumption (milk and meat), but the doses due to ingestion of those products are much lower than those due to the ingestion of tomatoes because of the filtering effect of the animals.

163. Some of the plutonium deposited on land was transferred to the Mediterranean Sea when the Almanzora River, which flows through the village of Palomares, flooded [G1]. This transfer, however, is not significant from a radiological point of view.

164. Near Thule, the high-explosive components of four weapons detonated in an airplane crash, contaminating about 0.2 km^2. About 10 TBq of plutonium was recovered in the surface layer of the snow pack, and about 1 TBq was estimated to be trapped in the ice [L1]. A radioecological investigation conducted during the summer of 1968, when the ice had broken up, showed that the accident had measurably raised the plutonium level in the marine environment as far as 20 km from the point of impact. The highest concentrations were found in bottom sediments, in bivalves and in crustacea. Larger animals such as birds, seals and walruses showed plutonium levels hardly different from the fallout background [A1, A2].

165. Accidents have also happened during the transport of nuclear weapons by sea. At least 48 nuclear weapons and 11 reactors have been reported to be lying on the ocean floor [E3]. The most serious losses were two nuclear-powered submarines, each carrying several nuclear weapons; one sank off the coast of Bermuda in October 1986 and the other in the Norwegian Sea in April 1989. Another loss occurred near the coast of Japan in 1965, when an airplane with a 1 Mt hydrogen bomb rolled off an aircraft carrier. No information has been reported on the number of deaths or on the extent of environmental contamination associated with those accidents that resulted in the loss of nuclear weapons. However, some information is available about an accident that took place aboard a missile-carrying nuclear submarine in July 1961 in the Atlantic Ocean [K8]. In that accident, a depressurization in the primary coolant of one of the two nuclear reactors led to substantial radioactive contamination in the submarine and to a reactor shutdown. To prevent reactor meltdown, a temporary emergency cooling system was fabricated; this required welding work to be carried out in the reactor compartment itself, which led to eight deaths within a few weeks of the accident [K8].

D. SATELLITE RE-ENTRY

166. In 1964, when a SNAP-9A satellite containing ^{238}Pu as a power source re-entered the atmosphere and then burned up, about 600 TBq of that radionuclide were injected into the stratosphere [H1]. A similar device re-entered the atmosphere intact, produced no releases and fell into the Pacific Ocean in April 1970. Another generator fell into waters off the coast of California in May 1968, when a weather satellite exploded during launch. It was recovered in October 1968. In January 1978, the Cosmos 954 satellite re-entered the atmosphere, partially burned and scattered debris in the Northwest Territories of Canada. Detailed information on the characteristics of the radioisotopes and reactor-powered devices used in satellites, as well as on the malfunctions that have occurred, has been gathered by OECD [O4].

167. The collective dose from the SNAP-9A re-entry may be evaluated by applying transfer coefficients to the released amount. The transfer coefficient P_{25} from deposition of ^{238}Pu to dose via the ingestion pathway has been estimated to be 0.6 nSv per Bq m^{-2} (Table 8). The transfer coefficient P_{02} for ^{238}Pu, which has a half-life 87.7 years, would be expected to be 5 kBq m^{-2} per EBq released (Figure III) for temperate latitudes. The dose commitment for these latitudes would then be estimated to be 0.6 PBq $\times$ P_{02} $\times$ P_{25} = 1.8 nSv. The hemisphere average is less by a factor of 1.5 and the opposite hemisphere average is less by a factor of 4. Since re-entry was in the southern hemisphere, the averages for the hemispheres are 1.2 nSv (south) and 0.3 nSv (north). The population-weighted world average is 0.4 nSv (89% of the population lives in the northern hemisphere). For the relatively long half-life of ^{238}Pu, a world population of 6 10^9 may be taken to apply to this exposure [U3]. The collective effective dose from the ingestion pathway due to the re-entry of the SNAP-9A is thus estimated to be 2.4 man Sv.

168. The transfer coefficient P_{25} for the inhalation pathway has an estimated value of 800 nSv per Bq m^{-2} (Table 8). The dose commitment for the southern hemisphere temperate region is thus 0.6 PBq $\times$ P_{02} $\times$ P_{25} = 2,400 nSv. The average values for the hemispheres are then 1,600 nSv (southern hemisphere), 400 nSv (northern hemisphere) and 530 nSv (world). The collective dose from the inhalation pathway, with a population of 4 10^9 applicable at the time of re-entry, is 2,100 man Sv. The inhalation pathway is the dominant contributor to the collective dose. This is comparable to the collective effective dose derived for ^{238}Pu produced in atmospheric nuclear testing, which released 0.33 PBq, about half the total of the satellite re-entry, but with injection mostly into the atmosphere of the northern hemisphere.

169. Similar procedures may be used to estimate the collective dose from the Cosmos 954 re-entry. The fuel core was estimated to contain 20 kg of enriched uranium [G3]. With a steady power output of 100 kW over the 128 day lifetime of the satellite, the burn-up of the fuel was estimated to be 2 10^{18} fissions per gram of uranium [G3]. The estimated radionuclide inventory in the core at re-entry is presented in Table 57 [T6]. From analysis of recovered debris, it has been assumed that 75% of the radionuclide amounts were dispersed in the high atmosphere on re-entry of the space craft and 25% was deposited on the ground in the uninhabited impact area. The absence of the volatile elements iodine and caesium in surface samples indicates that 100% of the radionuclides of

these elements were dispersed on burn-up of the fuel core in the atmosphere. The collective dose is estimated in Table 57 from the widely dispersed material using the transfer factors of Figure III and Table 8. The result is 16 man Sv, mainly to the population of the northern hemisphere from ^{137}Cs and ^{90}Sr and over a longer term from ^{239}Pu.

E. INDUSTRIAL AND MEDICAL SOURCES

170. Three notable accidents involving small sealed sources used for industrial or medical purposes have occurred since 1982 [U1]. In December 1983, at Ciudad Juarez, Mexico, a non-licensed teletherapy source containing 16.7 TBq of ^{60}Co was sold to a scrapyard [M4]. It is believed that the source was broken and that its 6,000 pellets began to be dispersed during transport [M4]. The consequences of this accident were the contamination of thousands of tonnes of metallic products that were sold in Mexico and the United States, as well as the contamination of several foundries and streets and hundreds of houses. About one thousand people were exposed to substantial levels of radiation. It is estimated that seven persons received between 3 and 7 Sv; 73 persons received between 0.25 and 3 Sv, and 700 persons received between 0.005 and 0.25 Sv [M4]. There were no deaths.

171. In 1984, at Mohammedia, Morocco, a source of ^{192}Ir used to make radiographs of welds at a construction site became detached from the take-up line to its shielded container. The source dropped to the ground and was noticed by a passer-by, who took it home. Eight persons, an entire family, died from the radiation over-exposure, having suffered doses of 8-25 Sv [I4, S10]. Estimates of doses to the individuals are unavailable, so only a rough approximation can be made of the collective dose. Assuming 10 Sv on average to each person, the collective dose to those who died would have been 80 man Sv.

172. In September 1987, at Goiania, Brazil, a 50.9 TBq ^{137}Cs source was inadvertently removed from a therapy unit and dismantled by junk dealers [C6, I5, R4, V1]. The therapy unit was located in the abandoned and partly demolished Goiania Radiotherapy Institute. The dismantling of the source resulted in localized contamination of an inhabited area of the city. As the result of the direct handling of the source or parts of it, either during its dismantling or subsequently, 129 people were exposed, either externally or internally. Some suffered very high external contamination owing to the way they had handled the caesium powder, such as having daubed their skin. Internal exposures resulted from eating with contaminated hands. The dose estimates varied from zero up to 5.3 Sv. Fifty-four persons were hospitalized and four died [I5]. The estimated collective doses were 56.3 man Sv from external exposures and 3.7 man Sv from internal exposures, including 14.9 man Sv (external) and 2.3 man Sv (internal) to the four persons who died [D9]. In the course of the decontamination programme, seven houses were demolished and large amounts of soil had to be removed. The total volume of waste removed was 3,100 m^3 [V1].

CONCLUSIONS

173. A number of events, activities or practices involving radiation sources have resulted in the release of radioactive materials to the environment. The consequent exposures of the population have been evaluated in this Annex. Estimates have been made of the total amounts of radioactive materials released in the event or since the beginning of the practice and of the collective doses that have been received or committed.

174. The most significant cause of exposure has been the testing of nuclear weapons in the atmosphere. A large number of tests were performed in the 1950s and to the end of 1962, with less frequent testing occurring until 1980, when the practice stopped altogether. The Committee has repeatedly evaluated the exposures from this source. The extensive measurements allow a rather systematic and complete assessment to be made. In this Annex the transfer coefficients that describe the movement of radionuclides in the environment to man and to the dose are summarized, extended and updated. The collective effective dose committed to the world population by atmospheric nuclear testing is estimated to be $3\ 10^7$ man Sv. Of this total, 86% is due to long-term, low-level exposure from ^{14}C. Over the next 10,000 years a collective dose of $2.2\ 10^7$ man Sv will have been received. This value is recorded in Table 58, which summarizes the estimated collective doses from all sources.

175. The underground testing of nuclear weapons does not generally cause the population to be exposed to radiation. It is only when there is some leakage or venting of gases or aerosols, as has occurred on some occasions, that relatively low exposures may result. The Committee estimates the collective effective dose

from underground testing to be of the order of 200 man Sv.

176. The Committee has not previously estimated the exposures of populations that result from the production of materials and the fabrication of nuclear weapons. Data are still not readily available, but initial estimates of collective doses have been made, namely of the order of 24,000 man Sv to local and regional populations and 40,000 man Sv from global, long-term exposure. Efforts are under way to reconstruct exposures that occurred in the early years of this activity, so some refinement and extension of the estimates can be anticipated.

177. A major activity utilizing radioactive materials is the generation of electrical energy with nuclear reactors. The release of radionuclides during routine operation of the nuclear fuel cycle is relatively low, however, and the doses can only be calculated using representative models for the sites and the dispersion processes through the environment. The releases and collective doses since the beginning of the practice in the 1950s have been at least two orders of magnitude less than those for atmospheric nuclear testing. The global, long-term collective effective dose to be received within 10,000 years is estimated to be 400,000 man Sv. Twenty-five per cent of this is due to ^{14}C released from reactors and reprocessing plants and 75% is due to ^{222}Rn released from uranium mill tailings piles.

178. A number of radioisotopes are used for industrial, educational and medical purposes. Those used in solid forms may not be released from end-uses; however, the gases, tritium, ^{14}C and radioiodines can be expected to be eventually released and dispersed. Data are generally unavailable on production amounts and release fractions of the radionuclides. Based on assumed values, the Committee estimates the global, long-term collective effective dose from this source to be 80,000 man Sv, with negligible contributions from all radionuclides except ^{14}C.

179. The accidents that have resulted in environmental contamination and exposures of population groups include those at civilian nuclear reactors (Three Mile Island and Chernobyl), at military installations (Windscale and Kyshtym), those that occurred in the transport of nuclear weapons (Thule and Palomares) and in satellite re-entry (SNAP-9A and Cosmos 954) and those that involved the loss or misuse of industrial and medical sources (Ciudad Juarez, Mohammedia and Goiania). With the exception of the Chernobyl accident and the re-entry of satellites, the environmental contamination has been localized, and for all except the Chernobyl accident the collective radiation doses have been relatively low. Nevertheless, injuries and deaths have resulted from some of these accidents.

180. The total collective dose from all sources of man-made environmental exposures is dominated by atmospheric nuclear testing. This source contributes 95% of the total collective dose indicated in Table 58. The annual collective effective dose to the world's population from natural sources of radiation exposure of 12,000,000 man Sv may help to put these estimates into perspective. Atmospheric nuclear testing was equivalent to three years of natural exposure of the world population at the time of the exposures. Other sources, of the order of a few tens or hundreds of thousands of man sievert, are comparable to hours or days of natural background exposure. The Committee has made the estimates in Table 58 with the objective of documenting each source of exposure and providing a perspective on the magnitudes of radionuclide releases and collective doses involved.